

LOFAR Cassiopeia A spectral line survey

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ABSTRACT

We use the Low Frequency Array to perform a systematic high spectral resolution investigation of the low-frequency 33–78 MHz spectrum along the line of sight to Cassiopeia A. We complement this with a 304–386 MHz Westerbork Synthesis Radio telescope observation. In this first paper we focus on the carbon radio recombination lines.

We detect $Cn\alpha$ lines at -47 and -38 km s^{−1} in absorption for quantum numbers $n=438$ – 584 and in emission for $n=257$ – 278 with high signal to noise. These lines are associated with cold clouds in the Perseus spiral arm component. $Hn\alpha$ lines are detected in emission for $n=257$ – 278 . In addition, we also detect $Cn\alpha$ lines at 0 km s^{−1} associated with the Orion arm.

We analyze the optical depth of these transitions and their line width. Our models show that the carbon line components in the Perseus arm are best fit with an electron temperature 85 K and an electron density 0.04 cm^{−3} and can be constrained to within 15% . The electron pressure is constrained to within 20% . We argue that much of these carbon radio recombination lines arise in the CO-dark surface layers of molecular clouds where most of the carbon is ionized but hydrogen has made the transition from atomic to molecular. The hydrogen lines are clearly associated with the carbon line emitting clouds, but the low-frequency upperlimits indicate that they likely do not trace the same gas. Combining the hydrogen and carbon results we arrive at a firm lower limit to the cosmic ray ionization rate of 2.5×10^{-18} s^{−1}.

Key words: ISM: clouds – radio lines : ISM – ISM: individual objects: Cassiopeia A

1 INTRODUCTION

Spectral lines resulting from atoms recombining with electrons in diffuse, ionised plasma are potentially important diagnostics to probe the conditions of the emitting and absorbing gas. At low quantum numbers recombination gives rise to the well-known optical and near-infrared recombination lines. At higher quantum numbers the energy spacing between subsequent quantum levels decreases and a recombination line transition will emit a photon at radio wavelengths. The associated lines for high quantum numbers are therefore called Radio Recombination lines (RRL).

RRLs can be used to obtain a wealth of information on the properties of the emitting gas (e.g. Gordon & Sorochenko 2009). Emitting in the radio domain,

these lines are unbiased by dust obscuration. At low radio frequencies (<1 GHz) RRLs provide us with a method to obtain temperature, density and ionisation of the cold neutral medium (e.g. Shaver 1975, 1976a,b; Sorochenko & Smirnov 1987; Payne, Anantharamaiah & Erickson 1989; Oonk et al. 2015). This information can not easily be obtained by other means, such as 21 cm neutral hydrogen measurements.

Our own Galaxy is a copious emitter of RRLs. These come in two flavours; (i) discrete RRLs and (ii) diffuse RRLs. Discrete RRLs are associated with common HII regions and dense photodissociation regions (PDRs). Here recombination lines from hydrogen, helium and carbon are seen (e.g. Palmer 1967; Roelfsema, Goss & Geballe 1989; Natta, Walmsley & Tielens 1994; Wyrowski et al. 1997; Kantharia, Anantharamaiah & Goss 1998; Konovalenko & Stepkin 2005). These are predominantly observed at frequencies above 1 GHz as the hydrogen and

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helium recombination lines trace the warm ($T_e \sim 10^4$ K), high-density ($n_e > 10 \text{ cm}^{-3}$) fully ionized gas, while the carbon recombination lines trace the warm (~ 500 K), dense ($n_H \sim 10^{3-6} \text{ cm}^{-3}$) gas in PDRs bordering compact HII regions or associated with reflection nebulae.

Diffuse RRLs, are associated with the lower density, colder interstellar medium (e.g. Konovalenko & Sodin 1980; Blake et al. 1980; Payne et al. 1989; Erickson et al. 1995; Kantharia & Anantharamaiah 2001; Oonk et al. 2014, 2015; Salgado et al. 2016a,b). Here typically only recombination lines from carbon (CRRL) are observed as the ionisation levels are too low to produce observable hydrogen and helium lines. Diffuse CRRLs are best observed at radio frequencies below 1 GHz due to stimulated emission and absorption. Whereas discrete RRLs have been studied in great detail, the properties of the cold gas associated with diffuse RRLs in our Galaxy is not well determined. Furthermore these diffuse RRLs provide us with a complementary tracer of the physical conditions in the cold neutral medium (CNM) of the Milky Way.

So far, the only line of sight studied in some detail for CRRLs is the one towards the bright supernova remnant Cassiopeia A (Cas A). This is because Cas A is one of the brightest low frequency radio sources in the sky (e.g. Baars, Mezger & Wendker 1965; Bridle & Purton 1968; Parker 1968), thus serving as a dominating background source, and it shows relatively bright CRRLs in both emission and absorption (e.g. Payne et al. 1989). The sightline towards Cas A cuts through the Milky Way at a galactic longitude $l = 112$ degrees and latitude $b = -2$ degrees. Cas A itself is located the 2nd Galactic quadrant in the Perseus spiral arm at a distance 3.4 kpc from the Sun and at a Galactocentric radius of about 10.5 kpc. HI 21 cm line observations show both emission and absorption in the range from +30 to -120 km s^{-1} (e.g. Mebold & Hills 1975; Bieging, Goss & Wilcots 1991; Schwarz, Goss & Kalberla 1997). The strongest HI absorption features are found around -47, -38 and 0 km s^{-1} . These are associated with foreground clouds in the Perseus (-47 and -38 km s^{-1}) arm and the Orion (0 km s^{-1}) spur. These clouds are also observed in other cold gas tracers such as CI (492 GHz) and CO (J=2-1) emission (e.g. Kilpatrick, Bieging & Rieke 2014; Mookerjee et al. 2006; Liszt & Lucas 1999; Anantharamaiah, Erickson & Payne 1994).

The CRRLs along this line of sight have been studied by e.g. Payne et al. (1989), Anantharamaiah et al. (1994), Kantharia, Anantharamaiah & Payne (1998) and Gordon & Soroichenko (2009). It was found that the CRRLs show a good correspondence with HI absorption, both in velocity and in distribution, and somewhat less good with CO (J=2-1) emission. Attempts were made at modeling the CRRL line properties as a function of quantum number n to derive the physical parameters of the CRRL emitting gas (e.g. Payne et al. 1989; Kantharia, Anantharamaiah & Payne 1998). These investigations showed that the velocity averaged CRRLs from the Perseus arm favor warmer, lower density models (electron temperature $T_e \sim 75$ K and electron density $n_e \sim 0.02 \text{ cm}^{-3}$) over colder and denser models ($T_e \sim 30$ K and $n_e \sim 0.05$). However, a clear discrimination was not possible, as the models presented by Payne et al. (1989) and

Kantharia, Anantharamaiah & Payne (1998) were not able to simultaneously fit the >150 MHz CRRL emission in combination with the <150 MHz CRRL absorption. Furthermore the results they obtain from the line widths differed from those obtained from the optical depths. This is likely due to a number of factors; (i) the limited validity of the CRRL models used at the time, (ii) the difficulty in determining the total line profile at low frequencies and (iii) averaging over multiple velocity components with potentially different physical gas conditions.

Here we revisit the Cas A CRRL line of sight making use of new high quality, high spectral resolution interferometric data from the Low Frequency Array (LOFAR) and the Westerbork Synthesis Radio telescope (WSRT) to perform a velocity resolved study of the CRRLs. In addition we make use of our new CRRL models (Salgado et al. 2016a,b) to derive the physical conditions of the associated gas.

The data presented in this paper are part of the LOFAR Cas A Spectral Survey (LCASS). This ongoing survey is a dedicated (Directors discretionary time) programme aimed at performing the first detailed low frequency, high spectral resolution, interferometric LOFAR study of the cold interstellar medium along the well studied Cas A line of sight. The survey, when complete, will cover the entire frequency range accessible to LOFAR, i.e. 10-80 MHz, 110-190 MHz and 200-250 MHz, with a velocity resolution ranging from 11 km s^{-1} at the lowest frequency to 1 km s^{-1} at the highest frequency. The primary goal of LCASS is to provide a high signal-to-noise spectral line atlas and spatial maps of low-frequency CRRLs. In addition we will also search the low frequency spectrum for line emission and absorption from other atoms and molecules (e.g. OH and NO). The search for non-RRL lines will be presented in a future paper. In this paper we present the LCASS RRL results for the 33-78 MHz range.

The paper is structured as follows. In Sect. 2 we discuss the first LOFAR observations taken for the LCASS survey and the WSRT observations. The results are presented in Sect. 3. In Sect. 4 we fit our new CRRL models to the observations. We discuss the results in Sect. 5 and present our conclusions in Sect. 6.

2 OBSERVATIONS AND REDUCTION

2.1 LOFAR (33-78 MHz)

We obtained LOFAR LBA observations on December 27, 2011, from 10:00 to 20:30 UTC and October 31, 2013, from 11:55 to 21:55 UTC (Table 1). For each of these observations LOFAR's multi-beaming capabilities were used to place half of the available instantaneous bandwidth on Cas A, 122 subbands each 0.1953 MHz wide, totaling about 24 MHz. The other 122 subbands were pointed towards Cyg A which served as a calibrator (Oonk et al. 2014). For both pointing centers we obtained complete frequency coverage between 33-57 MHz (2011) and 55-78 MHz (2013), although about two dozen subbands were corrupted due to issues with the LOFAR offline storage system. The LBA_OUTER configuration was used for the LBA stations. In this case 48 (of 96) LBA antennas are used, located mostly in the outer part of the 87 m diameter stations. All four linear correlation products were recorded (XX, XY, YX, YY) and each sub-band

was subdivided into 512 frequency channels. The integration time was 2 s.

For the 2011 observation we used nine remote and 22 core stations providing baselines between 90 m and 80 km. A first step in the data processing is the automatic flagging of radio frequency interference (RFI) with the AOFlogger (Offringa et al. 2010). We slightly decreased the default flagging thresholds to avoid flagging good data as Cas A and Cyg A have flux densities $> 10^4$ Jy in the observed frequency range. Typically, a few percent of the data was flagged due to RFI. After flagging we averaged the data to 4 s time steps to reduce its size. The data were calibrated with the Black-Board Selfcal (BBS) software system (Pandey et al. 2009). We used high-resolution 10 arcsec clean components models of Cas A (Fig.1) and Cyg A (McKean et al. in prep.) for calibration. These models were obtained from previous LOFAR observations around 70 MHz.

As the observations are pointed towards the two brightest sources on the sky, either Cas A or Cyg A dominates the total signal on all baselines. We made a copy of the 4 s data and averaged further down from 512 to 1 channel per subband. We then obtained gain solutions for all four correlations with BBS on a 4 s timescale. We assume the sources are unpolarized over the observed frequency range. The gain solutions found were then applied to the 512 frequency channel data and a final round of flagging was carried out with the AOFlogger. Channel cubes were made with *casapy*, imaging and cleaning each channel individually. The first 25 and last 25 channels of the data were ignored as they are too noisy. We chose briggs weighting (Briggs 1995) with a robust value of 0.5 to create images with a resolution ranging between 30×40 arcsec² and 40×60 arcsec². We then convolved all images from all subbands to a common resolution of 45×65 arcsec² and created an image cube for each subband.

For the 2013 observation we used 24 core stations and 14 remote stations. The data reduction was performed in the same way as for the 2011 data set. Due to a clock problem only 18 core stations were used in the final analysis of the observations. We chose briggs weighting with a robust value of 0.5 to create images with a resolution ranging between 215×255 arcsec² and 310×360 arcsec², the lower resolution being a consequence of using only 18 core stations. We then convolved all images from all subbands to a common resolution of 350×400 arcsec² and created an image cube for each subband.

2.2 WSRT (304-386 MHz)

We obtained WSRT P-band observations on January 28, 2012, from 08:29 to 20:28 UTC (Table 1). The observations were carried out in the Maxi-short configuration and Doppler tracking was turned off. We observed in frequency switching mode with 10 s sampling and 6 simultaneous 1.25 MHz subbands (IVC bands) each having 2048 channels (using re-circulation) and 2 polarizations (XX,YY). Each subband is centered near an expected CRRL line frequency and we observe 3 CRRL lines per setup where each line is covered twice with a different central frequency setting (typically offset by 0.3-0.4 MHz). In total we specified 8 spectral setups of 6 subbands and cover a total of 24 lines (all 22 α lines within the observed frequency range and 2 additional

β lines). Each spectral setup observed 10 minutes on-source and then changed to the next setup and after the last setup is done we return to the first setup. This way we cycled the spectral setups through the full 12 h observation and created similar UV and time coverage for each subband. The total observing time per subband was about 1.5 h.

The first step in the data reduction was the automatic flagging of RFI with the AOFlogger. A dedicated WSRT P-band flagging strategy was developed for this purpose. The data were then averaged down and calibrated with CASA (McMullin et al. 2007) using the high resolution 10'' clean components model of Cas A (Fig.1). Gain solutions were obtained for both polarizations on 10 s timescale. The gain solutions found were then applied to the 2048 frequency channel data and a final round of flagging was carried out with the AOFlogger. Channel cubes were made with *casapy*, imaging and cleaning each channel individually. We chose briggs weighting (Briggs 1995) with a robust value of 0.5 to create images with a resolution ranging between 60×65 arcsec² and 75×95 arcsec². We then convolved all images from all subbands to a common resolution of 80×100 arcsec² and created an image cube for each subband.

2.3 Spectral analysis and line stacking

From the WSRT 300-390 MHz and LBA 33-57 MHz image cubes we extract spatially integrated on-source spectra from an 8×8 arcmin² aperture centred on Cas A. For the LBA 55-78 MHz range we used a 14×14 arcmin² aperture centred on Cas A. The larger aperture for the 55-78 MHz data is necessary given the lower spatial resolution of this observation. The CRRL α ($\Delta n=1$) lines are clearly visible in the individual spectra for both LOFAR and WSRT. We investigated the overlapping subbands containing CRRLs between the two LOFAR observations and we find that the line profile parameters agree within errors.

We removed the edge channels from the spectra and fitted a low order polynomial to the line free channels to estimate the continuum. We then convert the spectra to optical depth units following Onk et al. (2014). The typical spectral RMS per channel, in optical depth units, are 5×10^{-4} , 6×10^{-4} and 4×10^{-4} for LOFAR 55-78 MHz, 33-57 MHz and WSRT respectively. The peak signal to noise for individual α lines in the LOFAR spectra is typically 7-9 for the -47 component and 2-4 for the -38 km s⁻¹ component. Similarly for WSRT the typical peak signal to noise is about 5 for the -47 and 1.5 for the -38 component.

We perform line spectra stacking to the obtain higher signal to noise line profiles necessary to measure the line optical depth and line full width at half maximum (FWHM) of each of the velocity components. The initial stacking of line spectra was performed as described in Onk et al. (2014). These stacked spectra contain on average 6 α lines in the WSRT range and 10 to 20 stacked lines in the LBA range (Table 2). Stacking these lines over small changes in n is allowed as we expect the RRLs to change slowly and smoothly in the observed frequency ranges.

The stacked WSRT spectra are shown in Fig. 2 and the line profiles are found to be Gaussian. The three velocity components at -47, -38 and 0 km s⁻¹ are narrow enough and sufficiently separated that we can fit them well with

individual Gaussians. There is an additional line feature at -55 km s^{-1} , likely due to RRLs from sulphur, that we blank prior to fitting the CRRLs. The results from the Gaussian fits are summarized in Table 3. A stacked spectrum containing all α lines in the WSRT range is shown in Fig. 3 and the results from the Gaussian fits to this spectrum are summarized in Table 4. This latter spectrum is only used for our investigation of the gas ionization using the hydrogen lines in Sect. 5.2.

For the LBA spectra there is strong line broadening with decreasing frequency, as expected from the Stark effect (e.g. Sect. 4.1). This leads to significant line blending for the -47 and -38 km s^{-1} components. Furthermore, this causes the line profiles to have Voigt profiles instead of Gaussian profiles. Voigt profiles are characterized by broad line wings. These broad wings can be affected by residuals in the continuum as well as nearby lines, such as CRRL β ($\Delta n=2$), γ ($\Delta n=3$) and δ ($\Delta n=4$) lines. In order to obtain the best possible fit we performed a different stacking procedure to optimize the continuum baseline in the LBA line spectra. This procedure is described in detail in Salas et al. (in prep.) and is similar to the procedure used by Stepkin et al. (2007) for their low-frequency CRRL spectra.

Here we shortly summarize the main aspects of this procedure. For each stack the spectra are first searched for CRRL α and β lines that are unblended with other lines and unaffected by RFI and bandpass roll-off. These lines were then stacked and fitted with Voigt profiles to create template line profiles. These profiles are subtracted from each (unstacked) line spectrum and the residual spectra are stacked to search and fit for the CRRL γ lines. These γ lines are then also subtracted from the individual line spectra and one final stack is performed to search and fit for the δ lines and also remove those from the individual line spectra. The residual baseline in the individual line spectra, where all α , β , γ and δ lines have been removed, are then baseline corrected by a polynomial of order 0. Using the baseline corrected spectra we repeated the stack of the lines.

This procedure is repeated 5 times on the LBA spectra by increasing the polynomial order by one in each step. Finally, stacked spectra with only one kind of transition are obtained by removing the corresponding best fit Voigt profiles from the individual spectra. The α line spectra resulting from this procedure are shown in Figs. 4 and 5. The baseline corrected, stacked line spectra are then fitted with Voigt profiles for each of the three velocity components. The results are summarized in Table 5. The line broadening continues to increase towards lower frequencies and below 40 MHz ($n=550$) it is no longer possible to robustly disentangle the -47 and -38 km s^{-1} components.

In Salas et al. (in prep.) we have verified this baseline correction procedure with detailed simulated LOFAR spectra that have the same resolution and noise characteristics as our observations and are processed in the same manner. In the LBA range studied here this baseline correction procedure provides only a minor improvement in our recovery of the line profiles. However, this procedure becomes increasingly important at frequencies below 33 MHz. This spectral line stacking procedure with baseline correction processing, as described above, is only used for the CRRL stacks as it removes all unidentified line features. Upperlimits to the un-

detected HRRLs, Table 6, are obtained from stacked spectra without these corrections applied.

3 RESULTS

The WSRT spectra clearly show that there are at least 3 CRRL velocity components in emission at -47 , -38 and 0 km s^{-1} relative to the local standard of rest (LSR), see Figs. 2 and 3. This is consistent with previous measurements by e.g. Payne et al. (1989, hereafter PAE89) and Kantharia, Anantharamaiah & Payne (1998, hereafter KAP98). In addition the WSRT spectra also show evidence for the presence of a weak line near -55 km s^{-1} . It is most prominent at the highest frequency stack, but observed at the 3σ level in all stacks (e.g. Fig. 2). A similar feature is not seen in HI absorption or CO emission spectra (e.g. Bieging et al. 1991; Mookerjee et al. 2006; Kilpatrick, Bieging & Rieke 2014) which makes it unlikely that it is associated with CRRL from another cold cloud at this velocity. A more likely explanation is that this feature is associated with RRL emission from sulphur (SRRL) and/or other elements at higher atomic numbers (sometimes referred to as XRRL or ZRRL) from the -47 km s^{-1} cloud.

Here we will focus on the CRRL and HRRL emission from the -47 and -38 km s^{-1} velocity components that arise in clouds situated in the Perseus arm. The -38 feature is rather broad and the WSRT spectra show tentative evidence that this feature may in fact consist of more than one component. This can also be seen in the asymmetric line profiles of CO emission (Kilpatrick, Bieging & Rieke 2014; Mookerjee et al. 2006; Liszt & Lucas 1999) and HI 21 cm absorption (Bieging et al. 1991; Schwarz et al. 1997). In particular the CO ($J=2-1$) emission spectrum from Liszt & Lucas (1999) and Mookerjee et al. (2006) shows two emission peaks, one at -40 and one at -36 km s^{-1} . For our current analysis we will treat the -38 feature as a single component.

The WSRT data also show the presence of hydrogen RRLs (HRRL). These lines are shifted by $+149.4 \text{ km s}^{-1}$ in the stacked CRRL spectrum (Fig. 3). This difference corresponds exactly to the difference in rest frequencies between the CRRL and HRRL lines. This is only the 2nd detection of HRRLs along this line of sight and our detection is at a lower frequency than the first detection at 420 MHz by Sorochenko & Smirnov (2010, ; hereafter SS10). This is the first interferometric detection and the first time that also the weaker -38 km s^{-1} component is detected. For the even weaker Orion spur CRRL component we did not detect the corresponding HRRLs. If the hydrogen to carbon RRL ratio in the Orion spur is similar to that in the Perseus arm components then this non-detection reflects that even higher signal to noise measurements are necessary to detect the HRRLs for the Orion component.

The HRRL line for the -47 km s^{-1} component has the same width as the corresponding CRRL line, indicating that they both arise in the same gas. However, we notice that the HRRL line for the -38 km s^{-1} component has a significantly narrower width than the corresponding CRRL line. This may constitute additional evidence that the -38 km s^{-1} CRRL component consists of multiple velocity components and that the HRRLs only trace part of this.

The observed CRRL LBA spectra also show 3 CRRL velocity components, but they appear in absorption, see Figs. 4 and 5. The relative LBA line centroids at -47, -38 and 0 km s⁻¹ (relative to LSR) are consistent with the CRRL emission from WSRT, however the linewidths in the LBA range are observed to strongly increase in width with decreasing frequency (i.e. increasing n). This is expected and in Sect. 4.1 we will model this with collisional and radiation broadening. For $n > 550$ the increase in linewidth of the -47 and -38 component becomes so large that deblending these components becomes degenerate and as such we will only consider the $n < 550$ measurements in our analysis. The good correspondence between the absorption in the LBA and the emission in WSRT (Fig. 6) indicates that all of the CRRL emitting gas is situated in front of CasA. HRRLs were not detected in the LBA spectra and 3σ upperlimits are presented in Table 6.

4 RRL MODELING

The CRRL α ($\Delta n=1$) transition spectra for both WSRT and the LBA allow us to distinguish at least 3 velocity components at -47, -38 and 0 km s⁻¹. The measurements for the 0 km s⁻¹ component, associated with the Orion spur, will be treated in a forthcoming paper. Here we will focus on interpreting the CRRL α transitions ($\Delta n=1$) emission from the -47 and -38 km s⁻¹ components that are known to arise from clouds in the Perseus spiral arm (e.g. PAE89). We will use the high signal to noise stacked line spectra for our analysis (Figs. 4, 5 and 2). These CRRL spectra provide us with two observables to be modeled, (i) the line width and (ii) the optical depth. Both depend on the physical conditions of the emitting gas. In following we will first model the line width and then the optical depth. We will use the new CRRL models from Salgado et al. (2016a,b; hereafter S16a,b). We find that combining the constraints from both observables is useful to disentangle the degeneracy between electron temperature, electron density and radiation field (see Sect. 4.3).

We adopt a homogeneous slab with constant density (n_e), temperature (T_e) and size (L_{CII}). Equivalently, we could have selected the emission measure instead of the size of the cloud. This slab is bathed in a radiation field characterized by $T_R \propto \lambda^\beta$ with $\beta=2.6$ and normalized in terms of $T_{R,100}$ the value of T_R at 100 MHz. The level populations are fully described by the atomic physics involved (S16a,b). Following Seaton (1959) and Brocklehurst (1970), we define the departure coefficient b_n of level n as the weighted sum of the b_{nl} values (S16a). Here $b_{nl}=N_{nl}/N_{nl}(LTE)$, with $N_{nl}(LTE)$ the level populations as given by the Saha-Boltzmann equation under local thermal equilibrium conditions. We also introduce β_n as the correction factor for stimulated emission following Brocklehurst & Seaton (1972) and S16a. The b_n and β_n fully determine the optical depth given by a set of physical conditions T_e , n_e and T_R . In principle, the intensity also depends on the temperature of the background source but, in our analysis, we will assume that the intensity scales directly with the optical depth. S16b have shown that this is in general the case for quantum levels above 200 and we verify this *a posteriori* in Sect. 4.3. In our analysis, we use the models developed by S16a,b which solve the statistical

equilibrium equations for arbitrary n and l levels in terms of the b_n and β_n as a function T_e , n_e and T_R fully self consistently. The gas density and temperature, together with the radiation temperature, also set the radiation and pressure line broadening at high n (S16a,b). We assume a filling factor of 1 for the CRRL emitting gas and address this point further in Sect.4.4.

Previous studies of CRRL lines have been analyzed following the models by Walmsley & Watson (1982) and Ponomarev & Sorochenko (1992). Because of the limited computer power available at that time, considerable approximations had to be made and these models are not appropriate for quantitative analysis (S16a). In particular, as compared to previous models, we note that the b_n values for the models by S16a approach 1 faster at high n , i.e. $n \gtrsim 500-600$, and as such the corresponding $b_n \times \beta_n$ values are smaller and have significantly flatter behavior at these high n .

We have used the models by S16a to create a detailed (T_e , n_e , T_R) model grid for fitting our measurements. This grid is sampled in steps of 5 K for T_e in the range 10-150 K and in steps of 0.005 cm⁻³ for n_e in the range 0.01 to 0.11 cm⁻³. In addition this grid is computed with a non-zero Galactic power law radiation field T_R that is specified as above. For all T_e and n_e combinations in our grid we computed the departure coefficients for 5 values of $T_{R,100}$ i.e. $T_{R,100}=800, 1200, 1400, 1600$ and 2000 K. This range in $T_{R,100}$ covers the range in expected values for the radio continuum temperature from the Milky Way along the line of sight to Cas A (e.g. Haslam et al. 1982; Landecker & Wielebinski 1970; Roger et al. 1999). We will fit our data using a chi-squared method on this grid while adjusting the size of the cloud.

4.1 Line width

The measured FWHM line width for CRRLs depends on the instrumental resolution and three physical broadening terms; (i) Doppler, (ii) collisional and (iii) radiation broadening (e.g. S16b; Shaver 1975). The Doppler term is independent of frequency and set by the turbulence of the gas. The Doppler broadening is determined from the WSRT data and literature data at higher frequencies. We find that our WSRT data in the 300-390 MHz range are consistent with previously measured linewidth at 560 MHz by KAP98 and show no evidence for line broadening. From this we conclude that the line width in this range is dominated by Doppler broadening and derive a Doppler line width of 3.4 km s⁻¹ for the -47 km s⁻¹ component and 6.8 km s⁻¹ for the -38 km s⁻¹ component (Table 3 and 4).

Whereas the WSRT data show constant line widths, dominated by Doppler broadening, the LBA data shows a clear increase in the FWHM with increasing n , as expected from pressure and radiation broadening. Having determined the Doppler contribution, which is modeled as a Gaussian, to the line profile we proceed to analyze the remaining line broadening in terms of pressure and radiation broadening. Both of these terms are modeled as Lorentzians and in order to properly recover the Lorentzian line wings we use the high signal to noise line profiles obtained from our line stacking procedure (Sect. 2.3). We find that the line widths for the highest frequency stack ($n=438$) in the LBA are still consistent with pure Doppler broadening, see also Fig. 6,

after which the Lorentzian contribution is found to increase and dominates the overall line profile for $n > 540$. The total Lorentzian contribution to the line profile as a function of n in the LBA range is presented in Table 5.

Collisional and radiation broadening are manifestations of the Stark effect and depend on the physical conditions of the gas and its environment in terms of the electron temperature T_e , the electron density n_e and the ambient radiation field T_R (e.g. S16b; Gordon & Sorochenko 2009; Walmsley & Watson 1982; Brocklehurst & Salem 1977; Shaver 1975). We use the formulation by S16b for both collisional and radiation broadening. Here we parameterize the radiation field in terms of a Galactic power law radiation field as defined in Sect. 4.

We fit the total Lorentzian contribution to the line width in terms of $T_{R,100}$ as function of T_e and n_e in the ranges $T_e = 10\text{--}310$ K and $n_e = 0.005\text{--}0.5$ cm^{-3} . To avoid uncertainties from severe line blending we use only the data below $n = 550$. The allowed parameter space is presented in Fig. 7. Within the allowed region of parameter space we find that there is no strong preference for a particular set of physical conditions, i.e. all allowed combinations provide similarly good (i.e. reduced $\chi^2 \sim 1$) fits to the data. The non-allowed, i.e. blanked, area in Fig. 7 shows the region of parameter space that would overestimate the observed line widths beyond the measurement errors.

For both velocity components constant $T_{R,100}$ values trace smooth curves in (T_e, n_e) space and curves of increasing $T_{R,100}$ move the allowed set of physical conditions to lower T_e and n_e values. Both pressure and radiation broadening have a very similar dependence on quantum number and hence fitting the data is degenerate (e.g. S16b; Shaver 1975). As both give rise to Lorentzian profiles, their contributions to the line broadening are additive. For any given radiation field, we can then subtract the radiation broadening component and derive the contribution required from pressure broadening. That will leave us with a relationship between the density and temperature of the gas, which is $n_e \propto T_e^{-0.5}$ (S16b). Figs. 7, 8 and 9 illustrate this for a number of different values for $T_{R,100}$. With increasing radiation field temperature, this relationship shifts down. As these figures demonstrate, a large fraction of the parameter space is not allowed.

We see in Sect. 4.2, that the opposite behavior is found upon modeling the integrated optical depth and therefore the constraints obtained from modeling the line width provide us with useful information that is able to break the degeneracy between the different physical parameters. Finally we note that not only do we find that the -38 km s^{-1} component has a broader Doppler contribution than the -47 km s^{-1} component, but also its Lorentzian contribution increases slightly faster with increasing n than the -47 km s^{-1} component. This may indicate that the physical conditions differ between the -47 and the -38 component, or alternatively that the -38 feature consists of multiple velocity components with potentially different physical conditions.

4.2 Optical depth

The measured CRRL integrated optical depth depends on T_e , n_e , T_R and L_{CH} or equivalently, the emission measure $\text{EM}_{\text{CH}} = n_e \times n_{\text{CH}} \times L_{\text{CH}}$ (e.g. S16a; PAE89; Shaver 1975).

CRRLs at low frequencies arise from quantum levels n that are not in local thermal equilibrium (LTE) and as such we need to evaluate the departure coefficients b_n and β_n . These departure coefficients also depend on T_e , n_e and T_R (e.g. S16a and references therein). Here we have used the models by S16a to create a detailed (T_e, n_e, T_R) model grid for fitting our measurements as described in Sect. 4.

In the following we perform a grid search to find the best (T_e, n_e) model describing the data, for each $T_{R,100}$ value, by optimizing the value of L_{CH} . In Sect. 3 we showed that the WSRT emission and LBA absorption spectra are consistent in terms of the observed absolute and relative velocity centroids of the different CRRL components (e.g. Fig. 6). In addition we found in Sect. 4.1 that the observed line widths can be modelled with single physical models across the entire range in n from 225 to 550. This indicates that it is likely that all of the emitting gas observed from the -47 and -38 km s^{-1} Perseus arm components is situated in front of Cas A and hence can be modeled across the entire range in n with a single value of L_{CH} for emission and absorption.

We have selected the $n = 301$ (-47 km s^{-1} component only) and $n = 309$ CRRL measurements from PAE89 and the $n = 225$ CRRL measurement from KAP98 to complement our WSRT and LOFAR measurements upon fitting the models. The other data presented by these authors overlaps with our measurements and is consistent with these. We have not added these other measurements as they are either unresolved in velocity or have much lower signal to noise as compared to our measurements. In addition we want to avoid systematic uncertainties by adding measurements obtained with very different observing parameters. Finally we will only consider measurements with n in the range 225 to 550 as for $n > 550$ it is not possible to reliably decompose the -38 and -47 km s^{-1} components and for $n < 225$ radiative transfer effects become important.

The results of our grid search, in terms of the 1, 2 and 3 sigma confidence limits are shown by the red, blue and green colored boxes in Fig. 8 and 9 for the different values of $T_{R,100}$. For the -47 km s^{-1} component we find no significant difference in the quality (i.e. reduced $\chi^2 \sim 1\text{--}2$) of the best fit for each of the 5 different $T_{R,100}$ values, but there is a systematic trend in that higher $T_{R,100}$ values require (slightly) higher values of T_e and n_e , see Fig. 8. This trend is the opposite of what we observed for our line width modeling in Sect. 4.1 and we will discuss this in more detail in Sect. 4.3. Considering the entire parameter space probed by our model grid for the -47 km s^{-1} component we find that only a very limited region in parameter space is allowed and that we can constrain T_e to be in the range $80\text{--}90$ K and n_e to be in the range $0.035\text{--}0.045$ cm^{-3} . However, the $T_{R,100}$ value is not well constrained by only considering the integrated optical depth.

For the -38 component we find similar trends as for the -47 component in that we obtain equally good fits for each of the 5 different $T_{R,100}$ values and higher $T_{R,100}$ values require (slightly) higher combinations of T_e and n_e to be allowed, see Fig. 9. Given the lower signal-to-noise of the -38 component the parameter space is slightly larger than for the -47 component. In particular we see that a larger range in both T_e and n_e is allowed. However, this allowed range opens up along a particular curve in (T_e, n_e) -space that traces an almost constant (electron) pressure p_e . We will discuss

this curve in more detail in Sect. 5.1. Considering only the integrated optical depth models we constrain T_e to be in the range 70-85 K and n_e in the range 0.030-0.045 cm^{-3} . The model fits for the -38 component are not as good as for the -47 component and have a reduced $\chi^2 \sim 4$ -5. In particular we note that the increase in integrated optical depth in the LBA range increases faster with increasing n than expected from the best-fit model.

4.3 Combining Line width and Optical depth

In Figs. 8 and 9 we have shown the independent constraints from both the line width and the optical depth in a single plot of T_e vs. n_e as a function of $T_{R,100}$. We note that the constraints from the integrated optical depth are much more stringent than those obtained from the line width. However, as stated above, the integrated optical depth does not constrain $T_{R,100}$ well. The line width does not provide very good constraints on either T_e , n_e or $T_{R,100}$, but we find that the allowed models for the line width move in an opposite direction in (T_e, n_e) -space as compared to the models for the integrated optical depth upon changing $T_{R,100}$. Therefore the combination of the integrated optical depth and line width does allow us to constrain $T_{R,100}$ and thus constrain T_e and n_e better.

Considering both measurements we find that the electron temperature and density for both components can be constrained to better than 15 percent at the 1σ confidence level, see Table 7. We find very similar conditions, $T_e \sim 85$ K and $n_e = 0.04 \text{ cm}^{-3}$, for both components. The background Galactic radiation field is marginally higher for the -38, as compared to the -47, component, but both are well within the range measured along the line of sight to Cas A (e.g. Haslam et al. 1982; Landecker & Wielebinski 1970; Roger et al. 1999). The line of sight path length L_{CII} for these physical conditions is found to be about 35 and 19 pc for the -47 and -38 components respectively. Here we have assumed that the singly ionized carbon n_{CII} density is equal to the free electron density n_e . The contribution of ionized hydrogen to n_e , based on the HRRL measurements, is found to be of the order of a few percent and will be discussed in Sect. 5.2. This path length implies CII column densities N_{CII} of 4×10^{18} and $2 \times 10^{18} \text{ cm}^{-2}$ and CII emission measures EM_{CII} of 0.06 and $0.03 \text{ cm}^{-6} \text{ pc}$, respectively. The results from the combined line width and optical depth constraints are summarized in Table 7 and shown in Figs. 10 and 11. The CII emission measure of both components, in terms of the associated free-free absorption, does not violate the observed low-frequency radio continuum turnover of Cas A (e.g. Kassim et al. 1995).

For both the line width and the integrated optical depth modeling we have also considered radiative transfer effects for the CRRLs along the line of sight to Cas A. Following the prescription in S16b we find that radiative transfer due to Cas A affects our measurements by less than one percent for $n > 225$ and as such does not affect our results.

4.4 Comparison to earlier studies

PAE89 previously performed a velocity resolved CRRL investigation of the -47 and -38 km s^{-1} clouds observed along

the line of sight to Cas A. As discussed in Sect. 3 our measurements and those of PAE89 are broadly consistent, albeit that PAE89 have considerably higher scatter and larger errors in their measurements as compared to our data set.

For the line width modelling both PAE89 and we considered a purely Galactic radiation field with a dilution factor of 1. PAE89 considered $T_{R,100} = 800$ K and Doppler widths of 6.7 and 5.9 km s^{-1} for the -47 and -38 km s^{-1} respectively. The emission line measurements by PAE89 and this work show that the Doppler width for the -47 km s^{-1} component is overestimated in the modeling by PAE89. Another difference in computing the line width between PAE89 and our work is that PAE89 use the Shaver (1975) formulation, whereas we use the updated formulation by S16b. Comparing these we find that S16b predicts lower linewidths for both collisional and radiation broadening for a given combination of T_e , n_e and T_R . For a Galactic radiation field with $\beta = 2.6$ the line FWHM from radiation broadening predicted by S16b is 24% lower and this difference is independent of quantum number n . The lower values obtained from S16b are due to a more accurate approximation of the oscillator strength by S16b as compared to Shaver (1975). In terms of pressure broadening the difference is largest at low n and decreases towards higher n . This results from a more detailed fitting to the collisional cross-sections in S16b as compared to Shaver (1975). For the physical conditions of interest here S16b predicts a FWHM which is about 15% lower at $n = 200$ and this decreases to 5% lower at $n = 600$, as compared to (Shaver 1975). The total difference in the FWHM thus amounts to about 30% upon considering both broadening terms and, in combination with the different Doppler width, explains the higher Galactic $T_{R,100}$ values that we obtain here.

PAE89 also performed an investigation of the integrated CRRL optical depths. Our WSRT optical depth measurements for both the -47 and -38 km s^{-1} component at $n \sim 267$ are about 20 percent larger than the measurements of PAE89. Given the lower signal to noise and narrow bandwidth of the spectra in PAE89 this difference can likely be attributed to uncertainties in the line fitting by PAE89 as well differences in observing parameters and their calibration. The LBA optical depths at $n = 438$ to $n = 448$ are slightly larger than the measurements of PAE89, but consistent within errors. At $n \sim 500$ the sum of our measurements for the -38 and -47 components agrees with the sum of the PAE89 measurements, however the optical depths assigned to each of the two components by PAE89 differs from ours. We find that the lower signal to noise and the factor 2 lower velocity resolution of PAE89 likely makes their deblending more uncertain. At even higher n , i.e. $n \sim 575$, we find that the sum of our -38 and -47 measurements agrees well with the high signal to noise measurement at 34 MHz by KAP98.

PAE89 performed a fit to their integrated CRRL optical depth measurements. They, and subsequent work by Payne et al. (1994) and KAP98, used the models by Walmsley & Watson (1982) as the basis for their fitting procedures. PAE89 concluded that these models did not provide a satisfactory fit to their data. In particular they noted that their models could not simultaneously fit both the low n emission and high n absorption measurements and as such they could not discriminate between cold ($T_e \sim 20$ K), high density ($n_e \sim 0.3 \text{ cm}^{-3}$) models and warm ($T_e \sim 100$ K),

lower density ($n_e \sim 0.05 \text{ cm}^{-3}$) models. As described in Sect. 4 the models by Walmsley & Watson (1982) are not appropriate for a quantitative analysis of the CRRL data.

Most of the previous CRRL optical depth measurements agree well with the new high signal to noise measurements presented here. However, a few of the previous measurements are at variance with our data and given their lower signal to noise we deem those measurements to be unreliable and excluded them from our analysis. We find that the models by S16a,b are able to fit both the CRRL line width and the optical depth measurements well over the range $n=225\text{--}550$ for a single set of physical parameters (Sect. 4.3 and Table 7). In our modeling of the optical depth we have assumed a filling factor of 1 for the CRRL emitting gas. This seems reasonable as Schwarz et al. (1997) and Liszt & Lucas (1999) show that both the HI 21 cm absorption and the CO ($J=2\text{--}1$) emission extend over the entire face of the remnant.

5 DISCUSSION

Since the study by PAE89 there have been two other detailed investigations of the CRRLs along the Cas A line of sight by Payne et al. (1994) and KAP98. Neither of these studies were able to fit both the integrated optical depths and the line widths of the CRRLs for a single set of physical parameters. This is likely due to the reasons outlined in Sect. 4.4. With the more detailed models by S16a,b we have shown in Sect. 4.3 that we are now able to obtain a satisfactory fit to both the linewidth and the optical depths.

The derived electron densities of $\sim 0.04 \text{ cm}^{-3}$ translate into a density of hydrogen nuclei of 286 cm^{-3} , adopting the gas phase carbon abundance of 1.4×10^{-4} (Cardelli et al. 1996; Sofia et al. 1997). This density is high compared to the typical density of diffuse clouds traced by the 21 cm HI line ($n_H \sim 50 \text{ cm}^{-3}$; Wolfire et al. 2003). However, they are quite comparable to densities derived for the well studied diffuse sight-lines of ζ Oph, ζ Per, and o Per where simultaneous modeling of the observations of many atomic and molecular species result in densities in the range of $200\text{--}400 \text{ cm}^{-3}$ (e.g. van Dishoeck & Black 1986; Viala, Roueff & Abgrall 1988).

The derived temperature of 85 K is well in the range of temperatures derived by the same studies as well as temperatures derived from HI 21 cm line studies (e.g. Mebold & Hills 1975; Dickey & Benson 1982; Dickey & Lockman 1990; Heiles & Troland 2003). The derived thermal pressure of $2 \times 10^4 \text{ K cm}^{-3}$ agrees, of course, well with those measured towards ζ Oph, ζ Per, and o Per but they are an order of magnitude larger than the typical gas pressures derived from UV absorption lines measuring the CI fine structure line excitation ($\sim 4 \times 10^3 \text{ K cm}^{-3}$; e.g. Jenkins & Tripp (2011)).

Finally, our sizes are comparable to the sizes of typical HI diffuse clouds ($\sim 10 \text{ pc}$, e.g. Spitzer 1978) but the derived column densities are an order of magnitude higher. These differences may merely reflect that we are probing clouds in the Perseus and Orion spiral arms rather than diffuse clouds in the local Solar neighborhood. Specifically, the clouds probed by the CRRLs may be the atomic/CO-dark surfaces of molecular clouds. As our clouds are situated in spiral arms and molecular clouds

have been detected along the same sight line at the same velocities (Bieging & Crutcher 1986; Liszt & Lucas 1999; Mookerjee et al. 2006; Kilpatrick, Bieging & Rieke 2014), this is quite reasonable.

The inferred pressures are also in line with measured pressures of molecular cloud surfaces (e.g. Blitz & Thaddeus 1980; Heyer, Carpenter & Snell 2001). Moreover, the very similar sight-lines towards ζ Per and o Per traverse the atomic HI surfaces associated with the B3/B4/B5 molecular clouds (Andersson, Roger & Wannier 1992). On the other hand, the high HI 21 cm column densities and the implied high visual extinction of these clouds ($N_{HI} \sim 2 \times 10^{22} \text{ cm}^{-2}$; $A_V \sim 10$ magnitudes) are very high for atomic clouds ($N_{HI} \lesssim 2 \times 10^{21} \text{ cm}^{-2}$; $A_V \lesssim 1$; e.g. Dickey & Lockman (1990)). Indeed, for visual extinctions in excess of 1 magnitude, much of the gas phase carbon is expected to be in CO (and to a lesser extent in CI) rather than CII (e.g. van Dishoeck & Black 1986; Viala, Roueff & Abgrall 1988). This may just be a matter of geometry as the clouds probed by the CRRL may be arranged into thin sheets as is common for large scale HI structures (Spitzer & Jenkins 1975; Sancisi et al. 1974; Heiles 1984). Future observations will be instrumental in settling the relationship between the CRRL gas and the molecular clouds in the direction of Cas A.

5.1 Gas pressure

In the previous sections we found that we can constrain the electron temperature and density for both components to better than 15 percent. If we consider T_e and n_e to be independent variables then this translates to an uncertainty of up to 20 percent for the electron pressure at the 1σ confidence level. One would expect the uncertainty on the pressure to increase at the 2 and 3σ levels, however this is not observed in Figs. 8 and 9. These figures show that T_e and n_e are not independent and that the electron pressure remains to be constrained to better than 20 percent at the 3σ confidence level. This tight relationship between T_e and n_e , along lines of almost constant pressure, is driven primarily by our constraints on the range in n where the CRRL emission to absorption transition takes place (Fig. 12).

Although the electron pressure itself is well constrained by our measurements there is still an uncertainty in translating this to a thermal gas pressure due to the unknown abundance of carbon in these clouds. The typical gas phase carbon abundance in the interstellar medium has been found to be $[C/H] \sim 1.4 \times 10^{-4}$ (e.g. Cardelli et al. 1996). It is possible to derive the carbon abundance $[C/H]$ by comparing CRRL measurements with HI 21 cm absorption measurements, under the assumption that the lines arise from the same gas and that within this gas singly ionised carbon is the dominant state of carbon, i.e. $N(\text{CII})/N(\text{HI}) \approx N(\text{C})/N(\text{H}) = [C/H]$ (e.g. Oonk et al. 2015, PAE89).

HI 21 cm absorption measurements have been carried out by e.g., Mebold & Hills (1975); Bieging et al. (1991); Schwarz et al. (1997). These studies find three main HI absorbing components at -47 , -38 and 0 km s^{-1} . These HI 21 cm components, in terms of velocity and FWHM, are in good agreement with our CRRL measurements and indicate that it is likely that the HI 21 cm absorption and our CRRL measurements spatially trace the same gas structures. A similar conclusion was reached by KAP98 (and ref-

erences therein). However, these studies also find that the HI 21 cm absorption measurements are heavily saturated for the -47 km s⁻¹ component and mildly saturated for the -38 km s⁻¹ component. This means that from these measurements we can only obtain a lower limit to true cold HI column density. Following Schwarz et al. (1997) find $N(\text{HI}) > 4 \times 10^{21} \text{ cm}^{-2}$ and $N(\text{HI}) > 3 \times 10^{21} \text{ cm}^{-2}$ for the -47 and -38 component respectively. An upperlimit to the HI column density can be obtained by considering the total hydrogen column $N(\text{H})$ from X-ray observations. The maximum total $N(\text{H})$ reported by Hwang & Laming (2012) is about $3.5 \times 10^{22} \text{ cm}^{-2}$. From these measurements we can only constrain the carbon abundance to be in the range $[\text{C}/\text{H}] = 1.3\text{--}11 \times 10^{-4}$ for the -47 component and $[\text{C}/\text{H}] = 0.7\text{--}7.7 \times 10^{-4}$ for the -38 component.

If we adopt the gas phase abundance by Cardelli et al. (1996) then we find a thermal pressure $p_{\text{thermal}}/k = 2.4 \times 10^4 \text{ K cm}^{-3}$. This is consistent with the model prediction of $p_{\text{thermal}}/k \sim 1 \times 10^4 \text{ K cm}^{-3}$ by Wolfire et al. (2003, their Fig. 7) for densities $n_{\text{H}} \sim 286 \text{ cm}^{-3}$ at a Galactocentric radius of about 10.5 kpc. It is also consistent with measurements and simulations of the external pressure for molecular clouds in the Galactic midplane (e.g. Blitz & Thaddeus 1980; Heyer, Carpenter & Snell 2001; Girichidis et al. 2016).

The turbulent pressure in the gas can be obtained from the observed FWHM of the turbulent (Doppler) line broadening. We calculate the turbulent velocity dispersion as $\sigma_{\text{turbulent}} = 3^{0.5} \times \text{FWHM}/2.355$ and find $p_{\text{turbulent}}/k = 1.9 \times 10^5 \text{ K cm}^{-3}$ for the -47 component and $p_{\text{turbulent}}/k = 7.6 \times 10^5 \text{ K cm}^{-3}$ for the -38 component. We thus find that the turbulent pressure dominates over the thermal pressure in both clouds as is typical in the interstellar medium of the Milky Way (e.g. Wolfire et al. 2003, and references therein).

Another contribution to the pressure in the clouds are magnetic fields. Using OH measurements Heiles & Stevens (1986) infer an average magnetic field strength $B \sim 8 \mu\text{G}$. HI 21 cm Zeeman splitting measurements by Schwarz et al. (1986) indicate an average parallel component of the magnetic field $B_{\parallel} \sim 20 \mu\text{G}$. The reason for the difference between these measurements is not clear. This range in measurements indicates a magnetic field pressure $p_{\text{magnetic}}/k = (1.8\text{--}4.5) \times 10^4 \text{ K cm}^{-3}$. This shows that the magnetic field pressure is of the same order as the thermal pressure and less than the turbulent pressure, although the HI measurements do allow for higher magnetic field pressures that may rival the turbulent pressure.

5.2 Gas ionisation

We have detected two HRRL emission lines in our stacked WSRT spectrum, see Fig. 3. This is the second detection of HRRLs along this line of sight. The first detection of HRRL emission at $n=250$ and associated with the -47 component was made by SS10 at 420 MHz. Our $n=267$ detection of this component at 344 MHz agrees well with theirs. For the -38 component, SS10 do not claim a detection, but they do see a feature in their spectrum. We confirm this feature here at the 4σ level. The main peak of our -38 HRRL line agrees well with the feature seen in the spectrum by SS10, however we do find that our line is narrower than theirs. Our -47 HRRL

line is also narrower than the detection reported by SS10, but not as much as for the -38 component. Line broadening of RRLs typically increases with increasing n , as discussed above, and this therefore does not explain the difference. The difference between our spectrum and SS10 is close to the noise level of the SS10 spectrum and their broader feature may be caused by a noise peak. Deeper observations are necessary to investigate this further.

The HRRL velocity centroids in our WSRT spectrum, in the rest-frame for hydrogen, are at -47.4 and -38.6 km s⁻¹. This agrees very well with the corresponding CRRL lines and shows that both the carbon and hydrogen lines likely originate in the same clouds, see Fig. 13. The line width of the CRRL and HRRL lines agree well for the -47 component, but the same is not true for the -38 component where our HRRL feature is significantly narrower than the corresponding CRRL feature (Fig. 13). This could indicate that only part of the -38 CRRL emitting gas is traced by the corresponding HRRL line.

Low frequency HRRLs can be used to trace the hydrogen ionization rates in the CRRL emitting clouds, if they trace the same gas. For the -47 component this is possible and two methods have been proposed to derive the total hydrogen ionization rate from HRRL measurements. The first method, proposed by Shaver (1976), uses the ratio between the HI 21 cm and the HRRL integrated optical depths. It is important to use the integrated and not the peak optical depths here, as the HRRL emission at sufficiently low frequencies can be affected by line broadening due to the Stark effect (e.g. S16b; Shaver 1975). In the previous section we saw that the HI 21cm absorption measurements are saturated and thus underestimate the true HI optical depth. This method therefore only provides an upperlimit to the ionization rate $\zeta_{\text{H}}(-47) < 5 \times 10^{-17} \text{ s}^{-1}$.

A second method to obtain ζ_{H} was first proposed by Sorochenko & Smirnov (1987), later modified by Sorochenko & Smirnov (1990) and SS10, and uses the ratio between the CRRL and the HRRL integrated optical depths. For convenience we repeat the equation here (as presented in SS10);

$$\zeta_{\text{H}} = \alpha_{\text{C}} \left(\frac{\tau_{\text{Hn}} \Delta\nu_{\text{Hn}}}{\tau_{\text{Cn}} \Delta\nu_{\text{Cn}}} \right) \left(\frac{\Phi_2 n_{\text{e}}}{T_{\text{e}}^{0.5}} \right) \left(\frac{(b_{\text{n}}\beta_{\text{n}})_{\text{C}}}{(b_{\text{n}}\beta_{\text{n}})_{\text{H}}} \right) \quad (1)$$

We use the b_{n} and β_{n} values from S16a. α_{C} is a numerical factor that depends on the carbon abundance $[\text{C}/\text{H}]$. For the gas phase abundance of carbon we have $\alpha_{\text{C}} = 3 \times 10^{-15}$ and find that $\zeta_{\text{H}}(-47) = 3 \times 10^{-18} \text{ s}^{-1}$. Following PAE89 we can also use the ratio of the HRRL to CRRL optical depth to estimate the volume density ratio of ionised carbon to protons ($n_{\text{CII}}/n_{\text{p}}$) and electrons ($n_{\text{CII}}/n_{\text{e}}$). Using our WSRT measurements at $n=267$ and the b_{n} , β_{n} values from S16a we find $n_{\text{CII}}/n_{\text{p}} = 15.5$ and $n_{\text{CII}}/n_{\text{e}} = 0.94$. This shows that 94 percent of the free electrons are donated by carbon.

The HRRL to CRRL hydrogen ionization rate we derive for the -47 component is an order of magnitude lower than reported by SS10. We find that this is entirely due to a difference in models used to compute the departure coefficients. We have also computed $\zeta_{\text{H}}(-47)$ from their $n=250$ measurement using our models and find that it is consistent with our measurement at $n=267$.

Our hydrogen ionization rate for the -47 component is

a factor of a few lower than the modeled cosmic ray ionization rate ($\zeta_{\text{CR},10 \text{ kpc}} \sim 1 \times 10^{-17} \text{ s}^{-1}$) and the EUV plus X-ray ionization rate ($\zeta_{\text{XR},10 \text{ kpc}} \sim 8 \times 10^{-18} \text{ s}^{-1}$) at a Galactocentric radius $R_c = 10 \text{ kpc}$ (Wolfe et al. 2003). Recent measurements of the cosmic ray ionization rate in diffuse clouds, through H_3^+ observations, by Indriolo & McCall (2012) have shown that the cosmic ray ionization rate is higher by almost an order of magnitude (i.e. $\zeta_{\text{CR}} \sim 10^{-16} - 10^{-15} \text{ s}^{-1}$) for total hydrogen column densities $N_{\text{H}} \leq 10^{22} \text{ cm}^{-2}$. This would be inconsistent with our measurement. However, Indriolo et al. made only a few measurements in the range $l = 90 - 130 \text{ deg}$, most of which are upperlimits, and for $N_{\text{H}} > 2 \times 10^{22} \text{ cm}^{-2}$ they find a steep drop to about $2 \times 10^{-17} \text{ s}^{-1}$ for the cosmic ray ionization rate.

Liszt (2003) furthermore points out that grain neutralization may lower the RRL derived ionization rates. In this case our RRL measurement would provide a firm lower limit to the actual ionization rate.

In the above calculation for $\zeta_{\text{H}}(-47)$ we have implicitly assumed that the CRRLs and HRRLs trace gas with the same physical conditions and the same geometry. To test this we plot in Fig. 14 the HRRL optical depth as a function of n with the HRRL models from S16a for the best-fit CRRL conditions overplotted. In order to fit the model to the data we allow the ionized hydrogen column density $N_{\text{HII}} = n_{\text{HII}} \times L_{\text{HII}}$ to differ from the singly ionized carbon column density $N_{\text{CII}} = n_{\text{CII}} \times L_{\text{CII}}$. If we demand HII and CII to follow the same geometry, i.e. $L_{\text{HII}} = L_{\text{CII}}$, then the HRRL to CRRL optical depth ratio directly traces $n_{\text{HII}}/n_{\text{CII}}$ i.e. the relative fraction of free electrons donated by hydrogen and carbon. In agreement with above we find $n_{\text{HII}}/n_{\text{CII}} = 0.06$.

Fig. 14 shows that for the -47 component the HRRL model with the best-fit CRRL gas conditions can match the high frequency detections by us, Oonk et al. (2015) and SS10, but not our low frequency 3σ LBA HRRL limits. This indicates that for the -47 component the CRRL and HRRL do not trace the same gas. To determine whether any other HRRL model can fit the HRRL measurements we ran a full HRRL grid search with the same parameters as done for the CRRLs above. We constrain the model fits by demanding that the model must be able reproduce all the detections within their 1σ errors and provide low frequency values that fall within the 3σ LBA limits. For the -47 component we find that only some significantly colder and higher density models, i.e. $T_e = 30 - 50 \text{ K}$, $n_e = 0.065 - 0.11 \text{ cm}^{-3}$ and $\text{EM}_H = 0.0007 - 0.002$, are able to fit the measurements.

This comparison of the HRRL and CRRL models suggests that the HRRL and CRRL emission may not originate in the same region with the same physical conditions. Alternatively, it is possible that the CRRLs probe CO-dark molecular gas (Sect. 5). In such gas carbon is ionized but hydrogen is in molecular form, a large contribution to the CRRL emission from CO-dark gas may then be expected. Spatially resolved investigations at higher frequencies (1-8 GHz) of dense PDRs have shown that in some cases narrow HRRL and CRRL lines do not trace the same gas (e.g. Roelfsema et al. 1989). Deeper and higher spatial resolution measurements are necessary to investigate this in cold clouds at low frequencies.

6 CONCLUSIONS

In this paper we present the first results from our ongoing LCASS radio survey of the cold ISM along the line of sight to Cas A. We have obtained high signal to noise observations with LOFAR in 33-78 MHz range and complemented these with WSRT observations in the range 304-386 MHz. The high signal to noise and high spectral resolution CRRL spectra allow us to carry out a detailed velocity resolved study of the foreground cold clouds in Perseus arm at -47 and -38 km s^{-1} . We have used our new CRRL models (S16a,b) to interpret the dependence of CRRL line width and integrated optical depth on quantum number n . For the first time we have found a set of physical parameters that can describe both the line width and integrated optical depth.

- The CRRL line width and optical depths for the -47 and the -38 components can be modeled as two uniform clouds. The best-fit model for the -47 km s^{-1} cloud has $T_e(-47) = 85 \pm 5 \text{ K}$, $n_e(-47) = 0.040 \pm 0.005 \text{ cm}^{-3}$, $L_{\text{CII}} = 35.3 \pm 1.2 \text{ pc}$ and $T_{\text{R},100} = 1351 \pm 81 \text{ K}$. The best-fit model for the -38 km s^{-1} cloud has $T_e(-38) = 85 \pm 10 \text{ K}$ and $n_e(-38) = 0.040 \pm 0.005 \text{ cm}^{-3}$, $L_{\text{CII}} = 18.6 \pm 1.6 \text{ pc}$ and $T_{\text{R},100} = 1507 \pm 128 \text{ K}$. The -38 km s^{-1} cloud has a steeper increase in optical depth at low frequencies, as compared to the -47 km s^{-1} cloud, and is fitted less well by our models. Together with the broad line profile this may indicate that the -38 km s^{-1} cloud consists of multiple velocity components with potentially different physical conditions.

- The derived CII column density is $(4.4 \pm 0.6) \times 10^{18} \text{ cm}^{-2}$ and $(2.3 \pm 0.3) \times 10^{18} \text{ cm}^{-2}$ for the -47 and -38 km s^{-1} clouds respectively. This is higher than in previous investigations as our $b_n \times \beta_n$ values for carbon from the S16a models are significantly lower than in previous models (e.g. Walmsley & Watson 1982; Ponomarev & Sorochenko 1992).

- The electron pressure, even for the lower signal to noise measurements of the -38 km s^{-1} cloud, is determined to better than 20% uncertainty out to the 3σ confidence level. The resulting thermal hydrogen pressure is $(2.4 \pm 0.5) \times 10^4 \text{ K cm}^{-3}$, if we assume the gas phase abundance of carbon. This pressure is high, but consistent with our expectations of dense clouds in the Galactic midplane at a Galactocentric radius of about 10.5 kpc.

- The detection of HRRLs with the WSRT allows us to assess that the ionized hydrogen to carbon ratio is about 0.06. This means that 94 percent of the free electrons are donated by carbon. The corresponding hydrogen ionization rate would be $(3 \pm 0.05) \times 10^{-18} \text{ s}^{-1}$ if the HRRL and CRRL trace the same gas. Our models indicate that this is not likely and much of the CRRL emission may be associated with CO-dark molecular gas. Deeper and higher spatial resolution measurements are necessary to investigate this further.

From our measurements and model we find a consistent picture for the -47 and -38 clouds in the Perseus arm towards Cas A, in that they are dense, cool clouds with very low hydrogen ionization levels. The saturated HI 21 cm absorption measurements prevent us from determining the carbon to hydrogen abundance for these clouds. We have here used

the gas phase abundance of carbon (i.e. $[C/H]=1.4\times 10^{-4}$) to convert our carbon measurements to hydrogen measurements. We find high thermal pressures and high hydrogen column densities ($N_H \sim 10^{22} \text{ cm}^{-2}$).

For these conditions we may be tracing the atomic to molecular hydrogen interface, and the gas cooling of such a cloud will be dominated by the [CII] 158 micron line (Wolfire et al. 2003, their Fig. 10). S16b shows that the [CII] 158 micron line can provide an independent constraint on the temperature if it traces the same gas as the CRRLs.

The work presented here shows that we can use low-frequency CRRLs to accurately determine the physical conditions of cold neutral clouds in the ISM. Future observations with LOFAR using LBA and also the High Band Antennas (HBA) will allow us to determine this for many other cold clouds making up the cold neutral medium and thus assess their role within the ISM and their relationship with molecular gas.

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Parameter	LOFAR LBA (1)	LOFAR LBA (2)	WSRT P-band
Data ID	L40787	L184343	S12A/002
Field center RA (J2000)	23h23m22.8s	23h23m22.8s	23h23m27.9s
Field center DEC (J2000)	+58d50m16s	+58d50m16s	+58d48m42s
Observing date	2011 December 27	2013 October 31	2012 January 28
Total on-source time	10.5 h	10 h	12 h
Frequency range	33-57 MHz	55-78 MHz	300-390 MHz
Number of sub-bands	122	122	6
Width of a sub-band	0.195 MHz	0.195 MHz	1.25 MHz
Channels per subband	512	512	2048
Channel width	2.0-3.5 km s ⁻¹	1.5-2.1 km s ⁻¹	0.5-1.0 km s ⁻¹

Table 1. Details of the Observations. Note that for WSRT we cycle through 6x8 spectral setups in time so that the on-source time per line amounts to about 1.5 h.

Stack	Species	Individual α line transitions	Observation
n		n	
260	C & H	257,258,260,261,262	WSRT
266	C & H	263,264,265,267,268	WSRT
271	C & H	270,271,272,273	WSRT
276	C & H	274,275,276,277,278	WSRT
438	C	435,436,437,438,439,440,442	LBA (2)
448	C	443,444,445,447,449,452,454	LBA (2)
459	C	456,457,459,460,461,463	LBA (2)
467	C	464,465,466,467,468,472	LBA (2)
477	C	473,474,475,479,480,481	LBA (2)
485	C	482,483,484,486,487,488,489	LBA (2)
496	C	491,492,493,495,496,497,498,499,500,501,503,504,505	LBA (1)
510	C	506,507,508,509,510,511,512,513,514,515,517,518,519	LBA (1)
527	C	522,523,525,526,528,529,530,531,532,533,534,535	LBA (1)
542	C	536,537,538,540,541,542,543,544,547,548,549,550	LBA (1)
559	C	551,552,553,554,558,559,560,561,562,563,565,566	LBA (1)
575	C	567,568,569,573,574,575,576,577,578,579,580,581,584	LBA (1)
439	H	435,436,437,438,439,440,441,442	LBA (2)
447	H	443,445,446,447,448,449,450,451	LBA (2)
458	H	454,455,456,457,458,459,460,461	LBA (2)
466	H	462,463,464,465,466,469,470,471	LBA (2)
475	H	472,473,474,475,476,477,478	LBA (2)
485	H	481,482,483,484,485,487,488,489	LBA (2)
496	H	491,492,493,495,496,498,499,501,502,503,504,505	LBA (1)
510	H	506,507,508,509,510,511,512,513,514,515,516,517	LBA (1)
527	H	519,522,523,525,526,528,529,531,532,533,535,536	LBA (1)
542	H	537,538,540,541,542,543,544,546,547,548,549,550	LBA (1)
559	H	551,552,556,557,558,559,560,561,562,563,565,566	LBA (1)
575	H	567,568,569,574,575,576,577,578,579,580,581,582,584	LBA (1)

Table 2. Individual α line transitions included in each CRRL and HRRL line stack.

transition	freq	$\int \tau d\nu$	v_{LSR}	FWHM _T
n	[MHz]	[Hz]	[km s ⁻¹]	[km s ⁻¹]
260	372.2	-8.54 ± 0.29	-47.71 ± 0.06	3.43 ± 0.13
		-4.85 ± 0.41	-38.81 ± 0.28	6.89 ± 0.69
266	347.6	-8.27 ± 0.28	-47.63 ± 0.05	3.24 ± 0.13
		-4.06 ± 0.42	-37.70 ± 0.36	7.10 ± 0.86
271	328.8	-8.48 ± 0.32	-47.76 ± 0.07	3.65 ± 0.16
		-4.23 ± 0.41	-38.24 ± 0.30	6.32 ± 0.72
276	311.2	-7.60 ± 0.24	-47.60 ± 0.05	3.24 ± 0.12
		-3.68 ± 0.34	-38.05 ± 0.31	6.93 ± 0.76

Table 3. WSRT P-band measured line properties for Cn α recombination line stacks.

RRL	Centre	FWHM	$\int \tau d\nu$	τ_{peak}
	[km s ⁻¹]	[km s ⁻¹]	[Hz]	
C	-47.67 ± 0.03	3.39 ± 0.08	-8.26 ± 0.16	$(21.5 \pm 0.5) \times 10^{-4}$
H	101.99 ± 0.14	3.81 ± 0.34	-1.96 ± 0.15	$(4.5 \pm 0.5) \times 10^{-4}$
C	-38.24 ± 0.18	6.78 ± 0.44	-4.19 ± 0.23	$(5.4 \pm 0.5) \times 10^{-4}$
H	110.80 ± 0.27	2.20 ± 0.63	-0.46 ± 0.11	$(1.8 \pm 0.5) \times 10^{-4}$

Table 4. WSRT stacked, over the full band, CRRL and HRRL α line profile properties for the line of sight to Cas A. The average frequency is 343.7 MHz which corresponds to $n=267$. The line centre, FWHM and integrated τ values are obtained from a Gaussian fit to the spectrum. The peak optical depth τ_{peak} is determined directly from the stacked spectrum that has 0.5 km s⁻¹ channels, see Fig. 3. The 1 σ spectral RMS per 0.5 km s⁻¹ channel is 0.5×10^{-4} in units of optical depth.

transition	freq	$\int \tau d\nu$	v_{LSR}	FWHM _T	FWHM _L	Observation
n	[MHz]	[Hz]	[km s ⁻¹]	[km s ⁻¹]	[km s ⁻¹]	
438	78.03	5.63 ± 0.50	-47.39 ± 1.46	5.60 ± 0.55	—	2
		1.75 ± 0.50	[-37.99]	7.41 ± 0.54	—	2
448	72.93	5.58 ± 0.27	-47.69 ± 1.57	5.56 ± 0.57	1.64 ± 0.30	2
		1.97 ± 0.21	[-38.29]	7.49 ± 0.54	—	2
459	67.82	6.15 ± 0.26	-47.66 ± 1.69	5.80 ± 0.57	1.75 ± 0.26	2
		2.89 ± 0.30	[-38.26]	8.10 ± 0.56	0.92 ± 0.94	2
467	64.39	6.61 ± 0.24	-47.69 ± 1.78	6.27 ± 0.57	2.31 ± 0.23	2
		2.96 ± 0.28	[-38.29]	8.61 ± 0.58	1.68 ± 0.88	2
477	60.43	6.81 ± 0.21	-47.86 ± 1.89	6.50 ± 0.57	2.42 ± 0.20	2
		3.79 ± 0.25	[-38.46]	9.11 ± 0.58	2.35 ± 0.65	2
485	57.49	7.30 ± 0.25	-47.95 ± 1.99	6.99 ± 0.57	2.95 ± 0.23	2
		(4.71 ± 0.34)	[-38.55]	(11.61 ± 0.67)	(6.06 ± 0.87)	2
496	53.76	7.47 ± 0.47	-46.10 ± 2.13	7.29 ± 0.60	3.10 ± 0.45	1
		3.82 ± 0.54	[-36.70]	9.47 ± 0.63	2.54 ± 1.33	1
510	49.45	7.97 ± 0.54	-45.89 ± 2.31	8.48 ± 0.63	4.44 ± 0.54	1
		4.41 ± 0.61	[-36.49]	10.57 ± 0.67	3.99 ± 1.30	1
527	44.82	8.82 ± 0.60	-46.02 ± 2.55	10.01 ± 0.66	6.09 ± 0.58	1
		5.13 ± 0.63	[-36.62]	12.01 ± 0.69	5.79 ± 1.11	1
542	41.21	8.74 ± 0.91	-45.95 ± 2.78	11.92 ± 0.75	8.19 ± 0.90	1
		6.16 ± 0.90	[-36.55]	14.52 ± 0.78	8.97 ± 1.21	1
559	37.57	(7.95 ± 1.00)	(-46.03 ± 3.04)	(12.76 ± 0.77)	(8.75 ± 0.99)	1
		(7.43 ± 1.00)	[-36.63]	(15.82 ± 0.75)	(10.30 ± 0.99)	1
575	34.52	(9.05 ± 1.34)	(-45.76 ± 3.31)	(15.17 ± 0.87)	(11.31 ± 1.22)	1
		(7.61 ± 1.29)	[-36.36]	(18.67 ± 0.82)	(13.58 ± 1.11)	1

Table 5. LOFAR LBA: Measured line properties for Cn α recombination line stacks. In our line profile fitting procedure we have fixed the velocity offset between the -47 and the -38 km s⁻¹ component to 9.4 km s⁻¹. For $n > 550$ the line blending of the two Perseus arm components is so severe that fitting two components, although necessary to describe the total line profile, is very sensitive to the local spectral noise and bandpass features. We therefore do not use decomposed optical depth and linewidth values for the individual component above $n=500$. Note that there is a small constant offset in velocity of 1-2 km s⁻¹ between the second LBA ($n=438-485$) and the first LBA ($n=496-575$) observations. This is due to the inaccuracies in our offline Doppler correction. We have not attempted to correct this as it does not influence the results for the integrated optical depth or the line width.

transition	freq	$\int \tau \, d\nu \, (3\sigma)$	v_{LSR}
n	[MHz]	[Hz]	[km s ⁻¹]
439	77.46	0.410	-47
		0.472	-38
447	73.38	0.212	-47
		0.246	-38
458	68.23	0.151	-47
		0.178	-38
466	64.78	0.140	-47
		0.163	-38
475	61.17	0.136	-47
		0.162	-38
485	57.46	0.111	-47
		0.143	-38
496	53.73	0.165	-47
		0.189	-38
510	49.43	0.163	-47
		0.182	-38
527	44.80	0.130	-47
		0.143	-38
542	41.19	0.108	-47
		0.119	-38
559	37.55	0.087	-47
		0.097	-38
575	34.50	0.110	-47
		0.122	-38

Table 6. Integrated optical depth limits (3σ) for the non-detected Cn α lines for hydrogen (HRRL) in the LOFAR LBA range. For the HRRL we use the stacked LBA spectra without baseline correction processing. The upperlimits for the integrated optical depth are calculated from $\tau_{rms,chn}$ and by assuming that the HRRLs are at the same velocity and have the same width as CRRLs.

Parameter	unit	-47 km s ⁻¹	-38 km s ⁻¹
T _{R,100}	[K]	1400 (1351 \pm 83)	1600 (1507 \pm 128)
T _e	[K]	85 \pm 5	85 \pm 10
n _e	[cm ⁻³]	0.040 \pm 0.005	0.040 \pm 0.005
L _{CII}	[pc]	35.3 \pm 1.2	18.6 \pm 1.6
EM _{CII}	[cm ⁻⁶ pc]	0.056 \pm 0.014	0.030 \pm 0.008
N _{CII}	[cm ⁻²]	(4.4 \pm 0.6) $\times 10^{18}$	(2.3 \pm 0.3) $\times 10^{18}$
N _H	[cm ⁻²]	(3.1 \pm 0.4) $\times 10^{22}$	(1.6 \pm 0.2) $\times 10^{22}$
n _H	[cm ⁻³]	286 \pm 36	286 \pm 36
p _{thermal} /k	[K cm ⁻³]	(2.4 \pm 0.5) $\times 10^4$	(2.4 \pm 0.5) $\times 10^4$
p _{turbulent} /k	[K cm ⁻³]	(1.9 \pm 0.1) $\times 10^5$	(7.6 \pm 1.0) $\times 10^5$
p _{magnetic} /k	[K cm ⁻³]	(1.8-4.5) $\times 10^4$	—
ζ_H	[s ⁻¹]	(0.3 \pm 0.05) $\times 10^{-17}$	—

Table 7. CRRL model results. Here we have adopted the gas phase abundance of carbon by Cardelli et al. (1996) to convert our CRRL measurements to hydrogen column densities N_H, volume densities n_H and thermal pressure. The range in magnetic pressures is taken from the measurements by Heiles & Stevens (1986) and Schwarz et al. (1986).

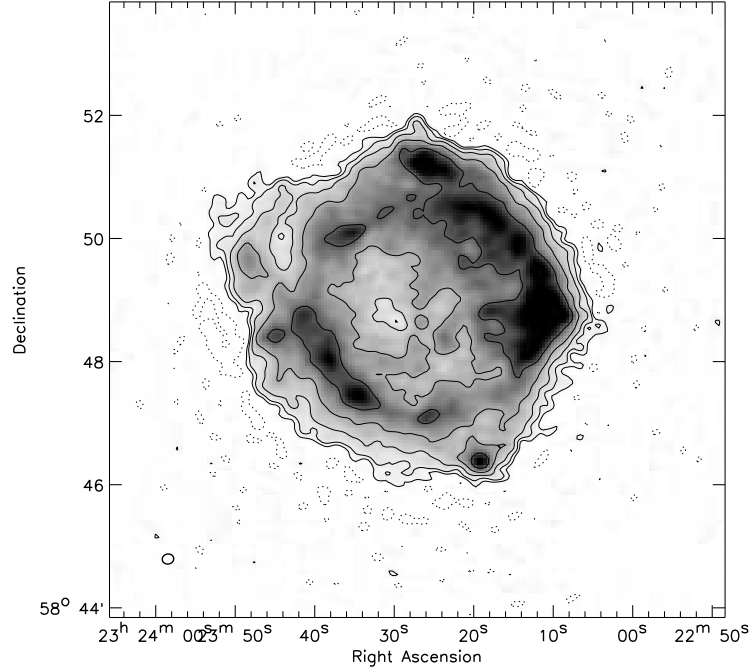


Figure 1. Cas A continuum image at 69 MHz obtained from a single 0.2 MHz sub-band. This image was made from a LOFAR LBA observation, taken on October 15th in 2011, using uniform weighting and has a resolution of $11.2'' \times 9.8''$.

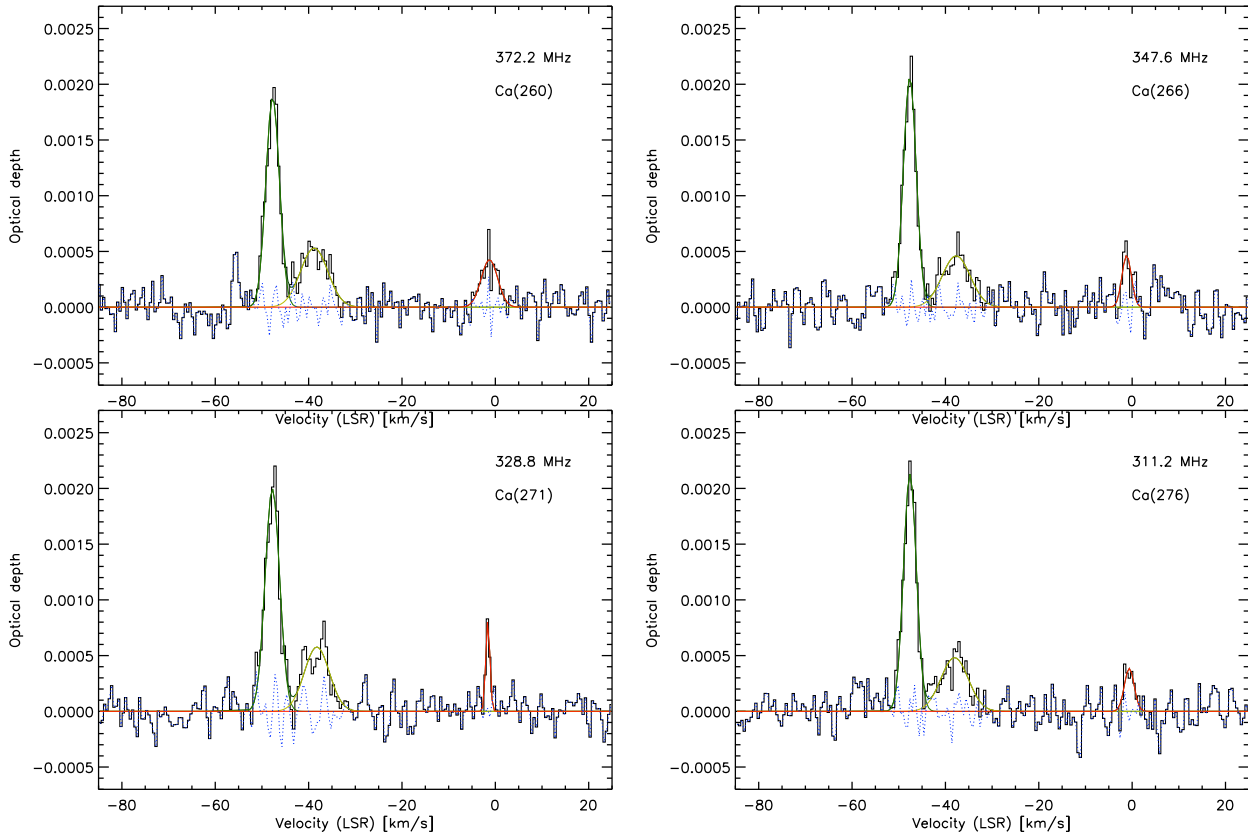


Figure 2. WSRT P-band 310-390 MHz: stacked CRRL spectra. The green, yellow and red lines show the decomposition into the -47, -38 and 0 km s^{-1} components. The blue dotted line shows the residuals after the subtracting the fitted line profiles.

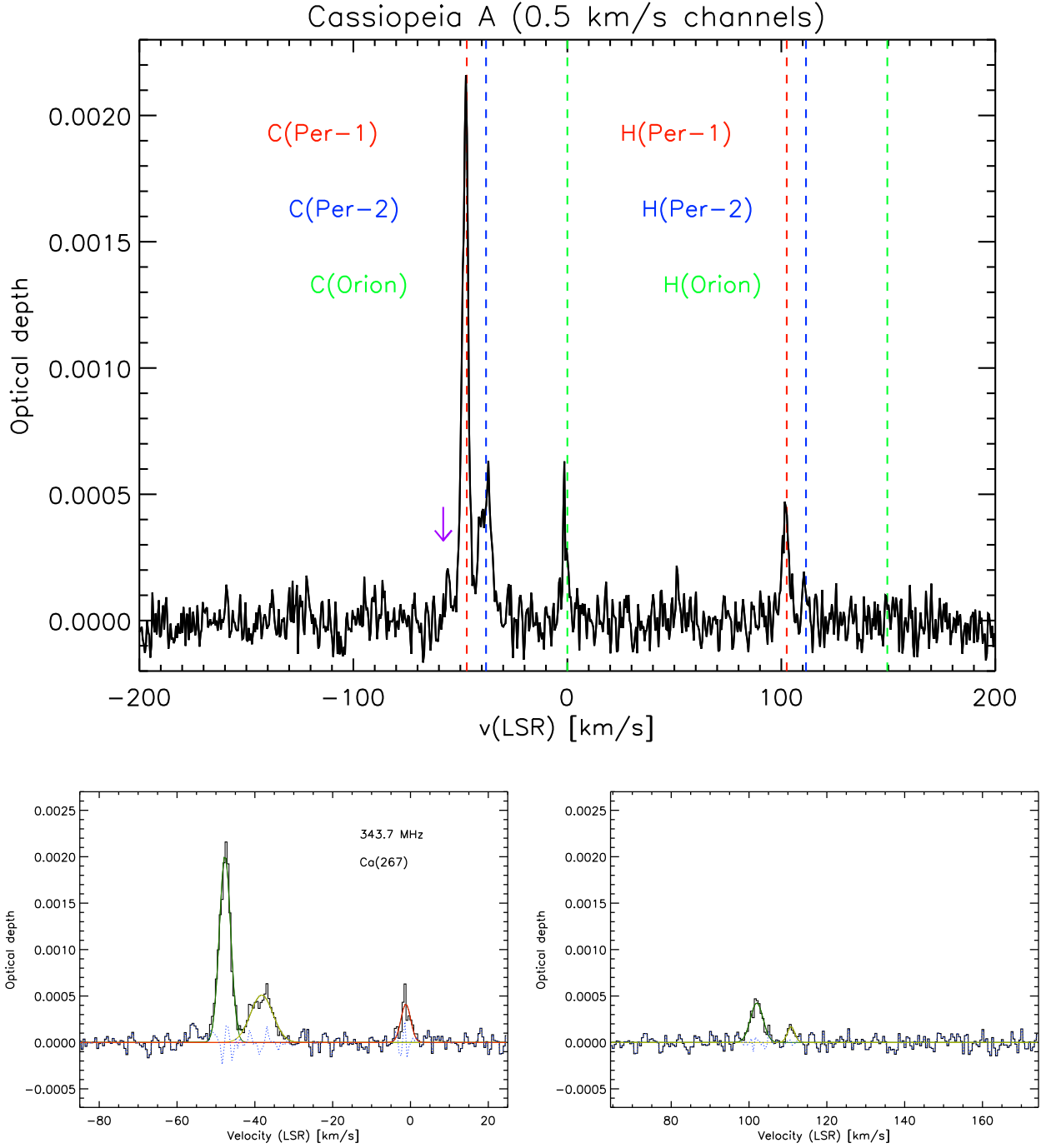


Figure 3. WSRT P-band stacked, over the full band, RRL spectra. The spectra are centered for CRRLs on $v(\text{LSR})=0.0 \text{ km s}^{-1}$ and spatially integrated over the remnant. Gaussian fits to the RRL lines are shown by the green (-47 component), yellow (-38 component) and red (0 component) solid lines in the bottom spectra. (*Top*) Stacked WSRT RRL spectrum showing both the CRRLs and HRRLs. The purple arrow shows the location of the SRRL feature at -55 km s^{-1} . (*Bottom-left*) Zoom in on the CRRL components. (*Bottom-right*) Zoom in on the HRRL components. In the bottom panels the green, yellow and red lines show the decomposition into the -47, -38 and 0 km s^{-1} components and the blue dotted line shows the residuals after the subtracting the fitted line profiles.

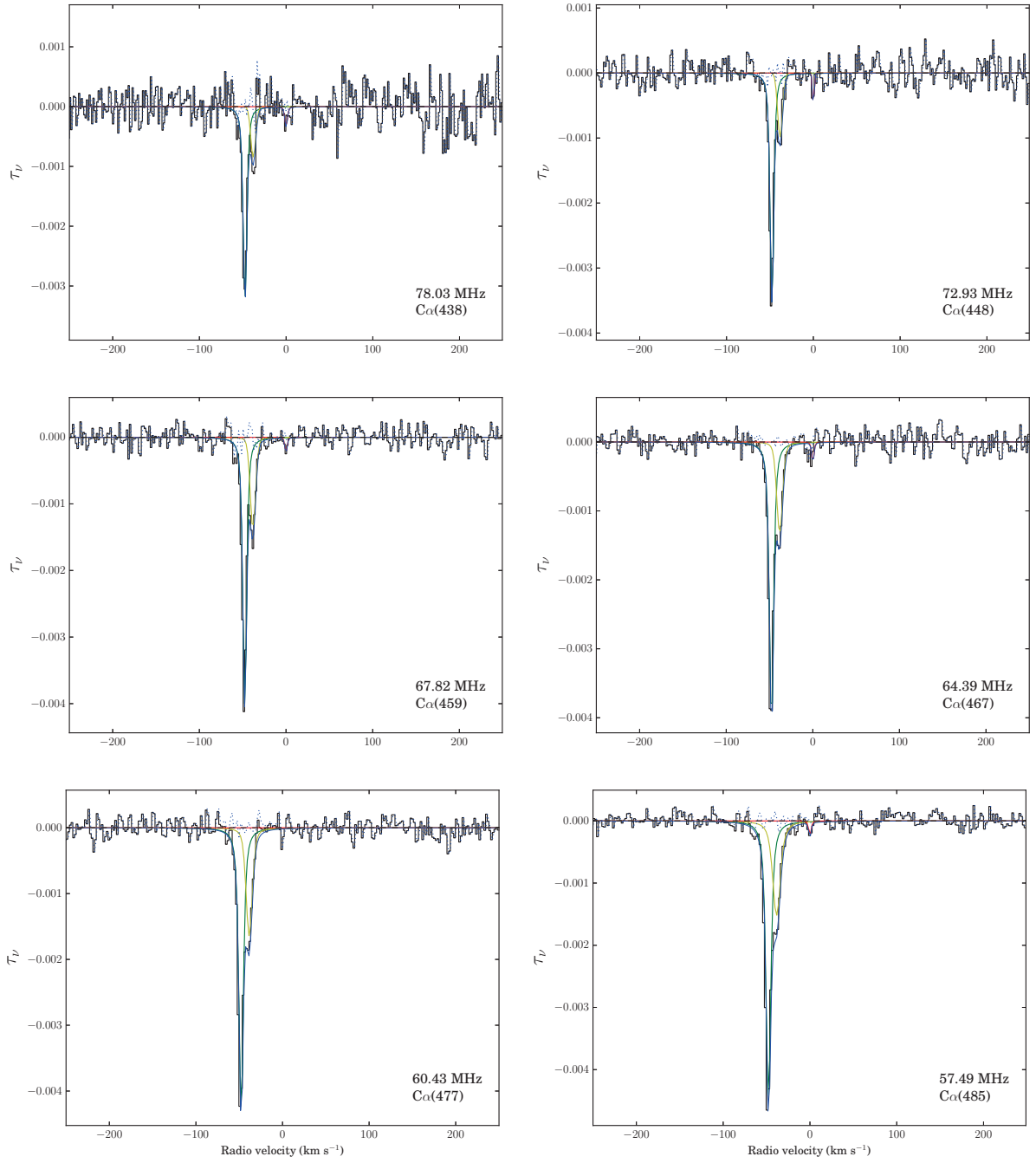


Figure 4. LOFAR LBA 55-78 MHz: stacked CRRL spectra. The green, yellow and red lines show the decomposition into the -47, -38 and 0 km s⁻¹ components. The blue dotted line shows the residuals after the subtracting the fitted line profiles.

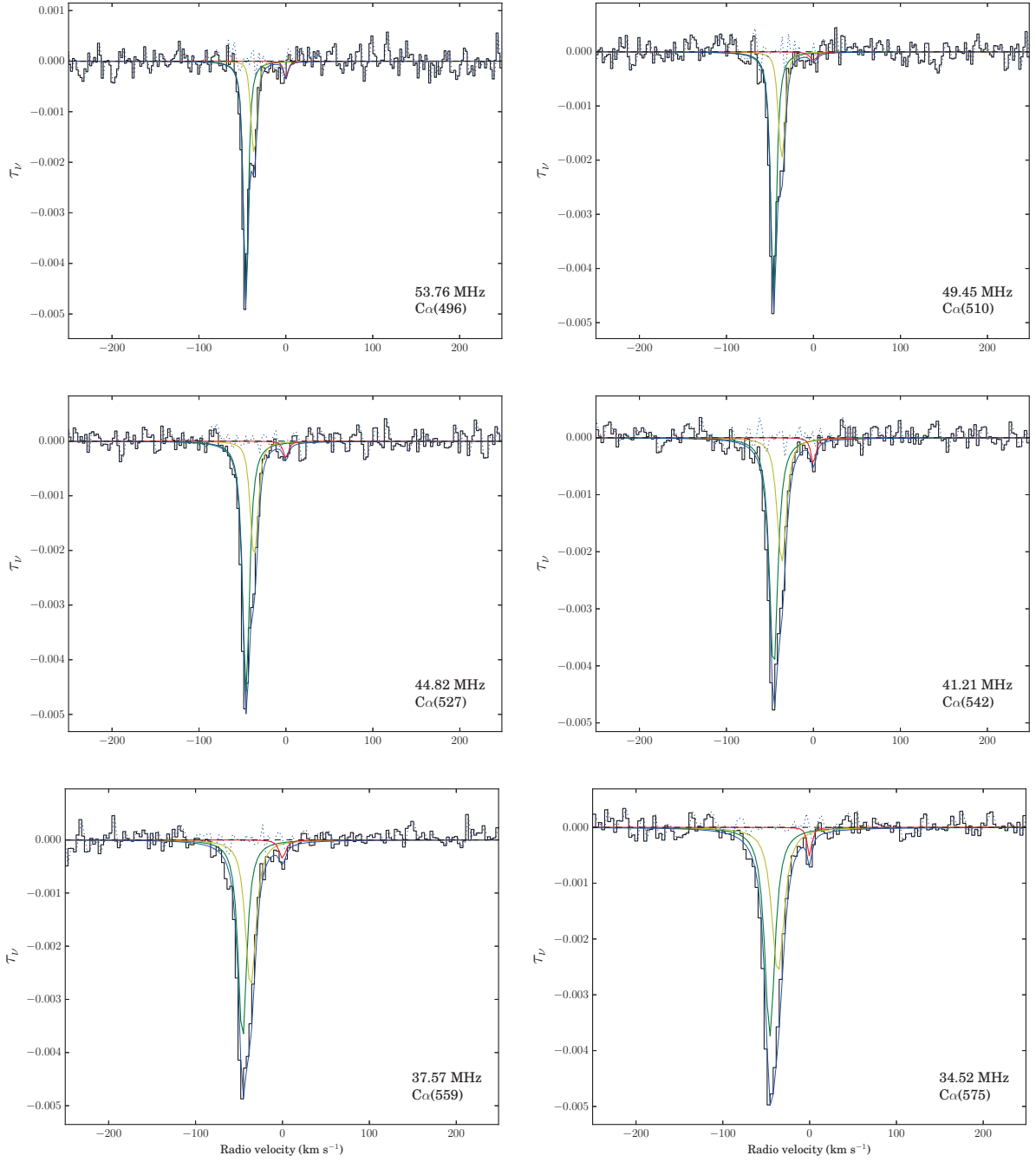


Figure 5. LOFAR LBA 56-33 MHz: stacked CRRL spectra. The green, yellow and red lines show the decomposition into the -47, -38 and 0 km s^{-1} components. The blue dotted line shows the residuals after the subtracting the fitted line profiles.

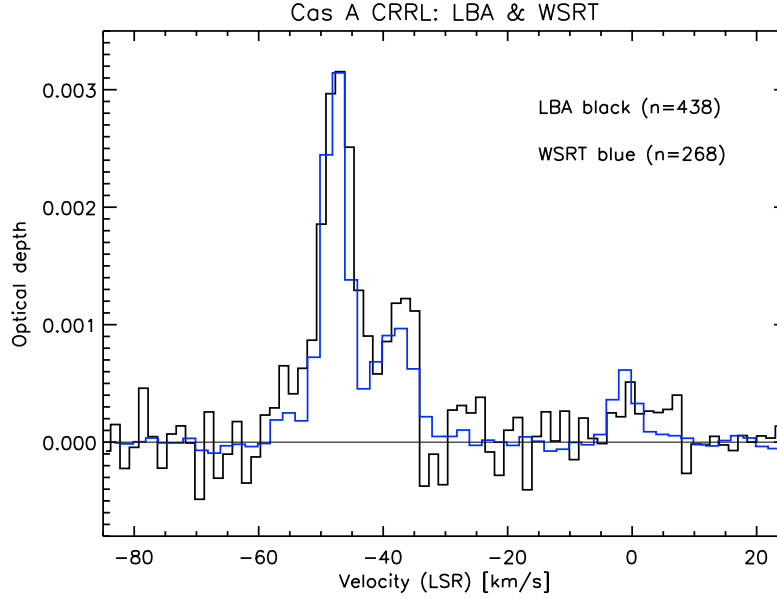


Figure 6. Overlay of the WSRT P-band ($n=268$, blue) and LBA ($n=438$, black) stacked CRRL spectra for the line of sight to Cas A. The LBA spectrum has been inverted for this comparison and the WSRT spectrum was re-scaled to match the peak of the -47 km s^{-1} component in the LBA spectrum. The good match of the line profile widths shows that at the highest LBA frequency the line profile is still dominated by Doppler broadening. Both the WSRT and the (unprocessed bandpass) LBA spectra show an excess at -55 km s^{-1} which could be associated with sulphur RRLs.

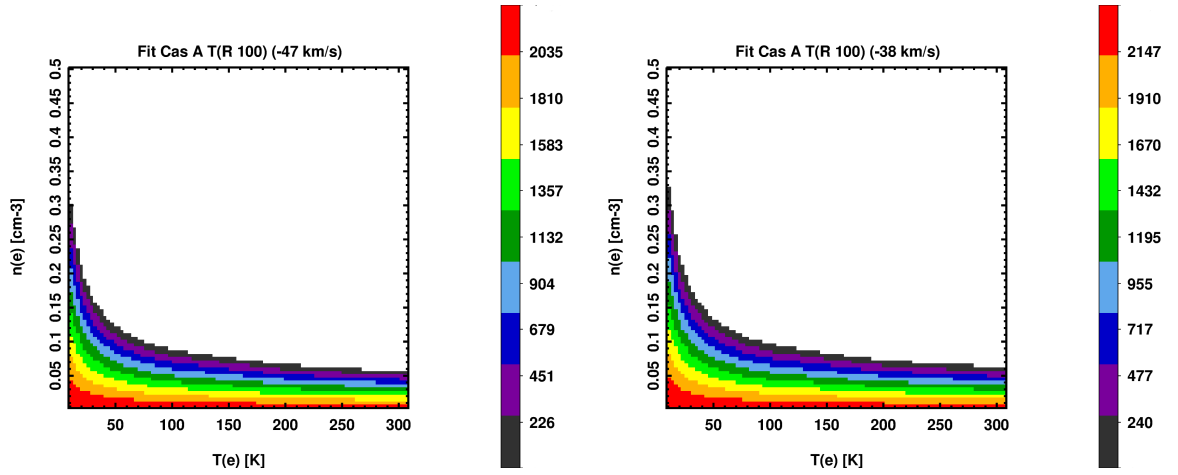


Figure 7. $T_{R,100}$ value as a function of T_e and n_e from our model fits to the CRRL line width (FWHM_L) vs. quantum number (n) for the Perseus arm components at -47 km s^{-1} (left) and -38 km s^{-1} (right). For the -47 km s^{-1} component we find that $T_{R,100}=1328 \text{ K}$ for the best-fit (T_e, n_e) combination from the optical depths, see also Fig. 10. For the -38 km s^{-1} component we find that $T_{R,100}=1507 \text{ K}$ for the best-fit (T_e, n_e) combination from the optical depths, see also Fig. 11. The reduced chi square values for the points shown for both the -47 km s^{-1} and the -38 km s^{-1} component are all around 1 showing the strong degeneracy between pressure and radiation broadening. The 1σ errors associated with $T_{R,100}$ are independent of (T_e, n_e) and found to be 83 K and 128 K for the -47 km s^{-1} and -38 km s^{-1} component respectively. Constant $T_{R,100}$ values trace curves of the form $n_e \times T_e^{-0.5}$.

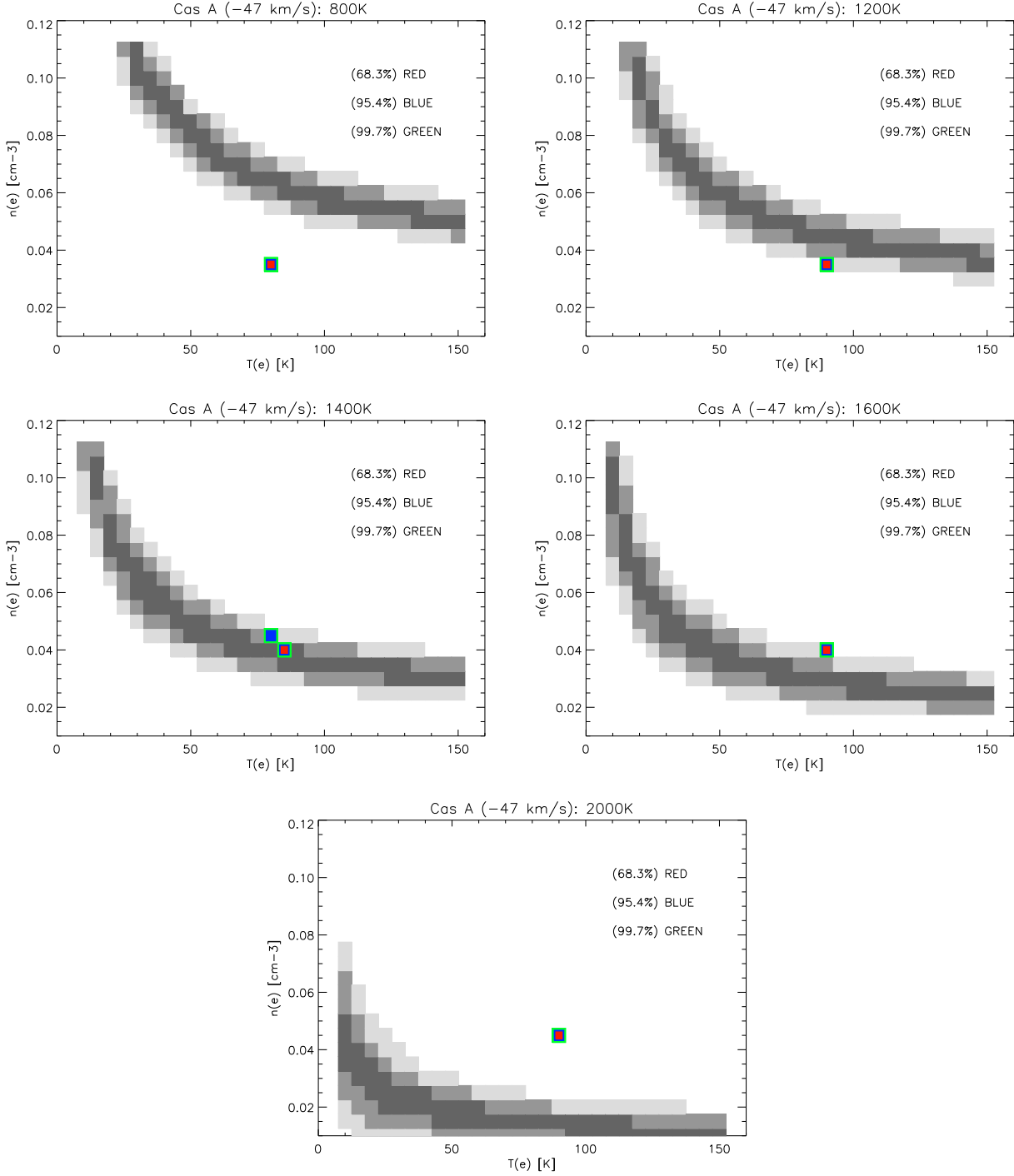


Figure 8. Combined model constraints for the CRRL integrated optical depth (τ) and line width (FWHM) for the Perseus arm component at -47 km s^{-1} . The 1, 2, and 3 sigma confidence limits from the integrated optical depth fitting are shown by the red, blue and green boxes respectively. The red and blue boxes should have the same size as the green boxes, but they have been decreased in size for clarity. The 1, 2, and 3 sigma line width error limits are shown by the black, dark-grey and light grey boxes respectively. The model fits shown have been carried out for five different Tr_{100} values of our (T_e, n_e) grid; (top-left) $\text{Tr}_{100} = 800 \text{ K}$. (top-right) $\text{Tr}_{100} = 1200 \text{ K}$. (middle-left) $\text{Tr}_{100} = 1400 \text{ K}$. (middle-right) $\text{Tr}_{100} = 1600 \text{ K}$. (bottom-left) $\text{Tr}_{100} = 2000 \text{ K}$.

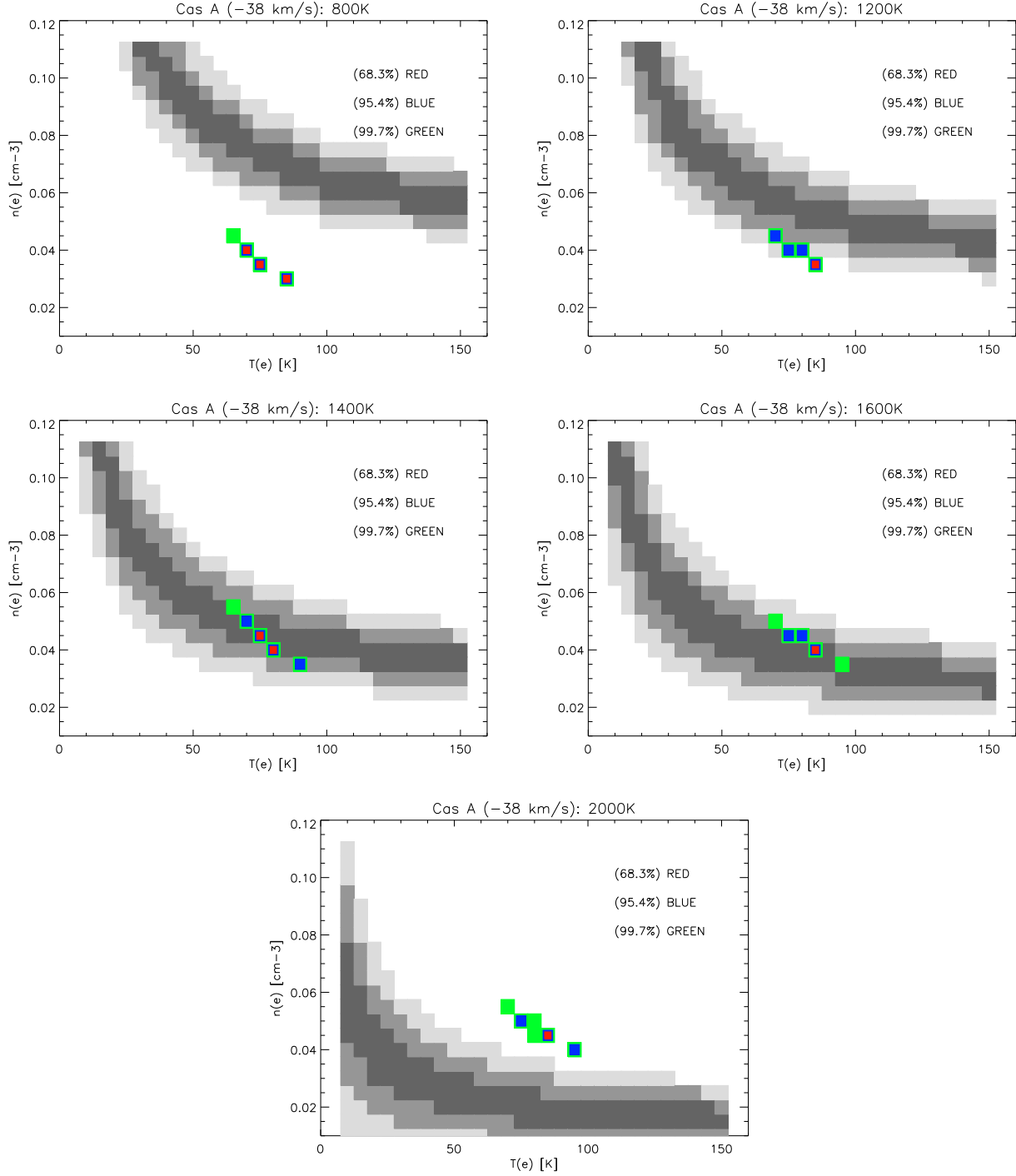


Figure 9. Combined model constraints for the CRRL integrated optical depth (τ) and line width (FWHM) for the Perseus arm component at -38 km s^{-1} . The 1, 2, and 3 sigma confidence limits from the integrated optical depth fitting are shown by the red, blue and green boxes respectively. The red and blue boxes should have the same size as the green boxes, but they have been decreased in size for clarity. The 1, 2, and 3 sigma line width error limits are shown by the black, dark-grey and light grey boxes respectively. The model fits shown have been carried out for five different Tr_{100} values of our (T_e, n_e) grid; (top-left) $\text{Tr}_{100} = 800 \text{ K}$. (top-right) $\text{Tr}_{100} = 1200 \text{ K}$. (middle-left) $\text{Tr}_{100} = 1400 \text{ K}$. (middle-right) $\text{Tr}_{100} = 1600 \text{ K}$. (bottom-left) $\text{Tr}_{100} = 2000 \text{ K}$. Our (T_e, n_e) grid is sampled in steps of 5 K for T_e in the range 10-150 K and in steps of 0.005 cm^{-3} for n_e in the range 0.01 to 0.11 cm^{-3} .

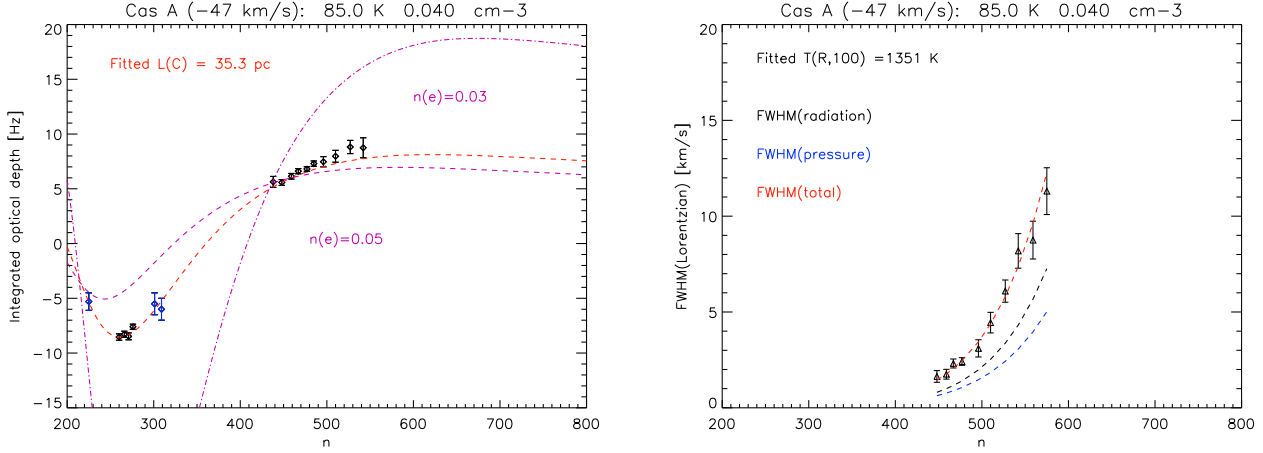


Figure 10. Best-fit CRRL optical depth and line width models overlaid on the measurements for the -47 km s⁻¹ component. Our LOFAR and WSRT data is shown in black. In addition we show the literature data that we have used in blue. The literature measurements are taken from Kantharia et al. (1998) and Payne et al. (1989) for $n = 225, 301$ and 309 . (left) The red curve shows the best-fit optical depth model with $L_C = 35.3$ pc for $T_{R,100} = 1400$ K. In addition we show in purple two optical depth models for the same best-fit T_e but with a 25 percent difference in n_e (dot-dash: $n_e = 0.03$ cm⁻³ and dashed: $n_e = 0.05$ cm⁻³). (right) The red curve shows the best-fit line width model with $T_{R,100} = 1351$ K. The red curves in both panels have the same T_e and n_e values that were taken from the best-fit CRRL optical depth model, see Fig. 8.

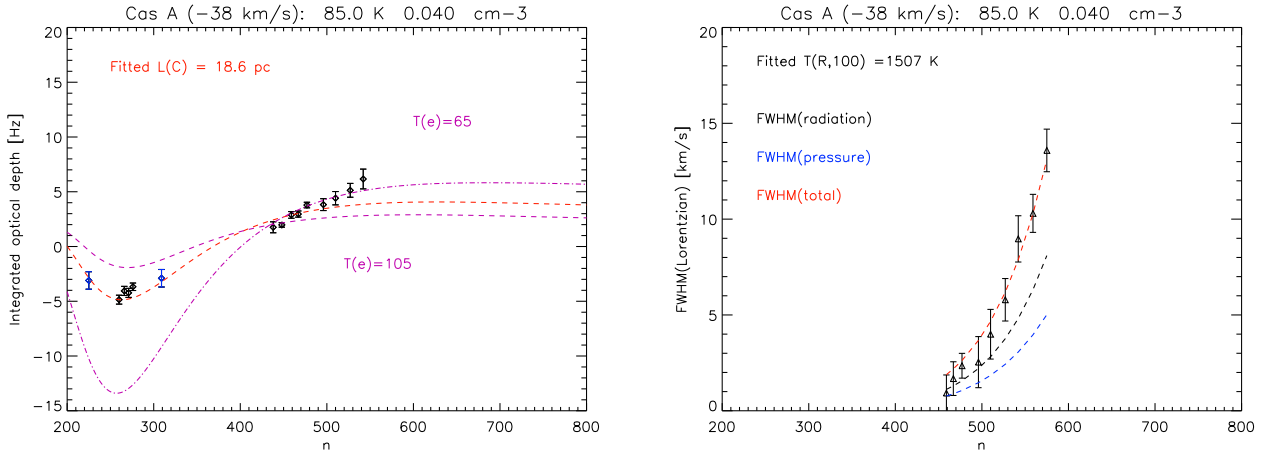


Figure 11. Best-fit CRRL optical depth and line width models overlaid on the measurements for the -38 km s⁻¹ component. Our LOFAR and WSRT data is shown in black. In addition we show the literature data that we have used in the fit in blue. The literature measurements are taken from Kantharia et al. (1998) and Payne et al. (1989) for $n = 225$ and 309 . (left) The red curve shows the best-fit optical depth model with $L_C = 18.6$ pc for $T_{R,100} = 1600$ K. In addition we show in purple two optical depth models for the same best-fit n_e but with a 25 percent difference in T_e (dot-dash: $T_e = 65$ K and dashed: $T_e = 105$ K). (right) The red curve shows the best-fit line width model with $T_{R,100} = 1507$ K. The red curves in both panels have the same T_e and n_e values that were taken from the best-fit CRRL optical depth model, see Fig. 9.

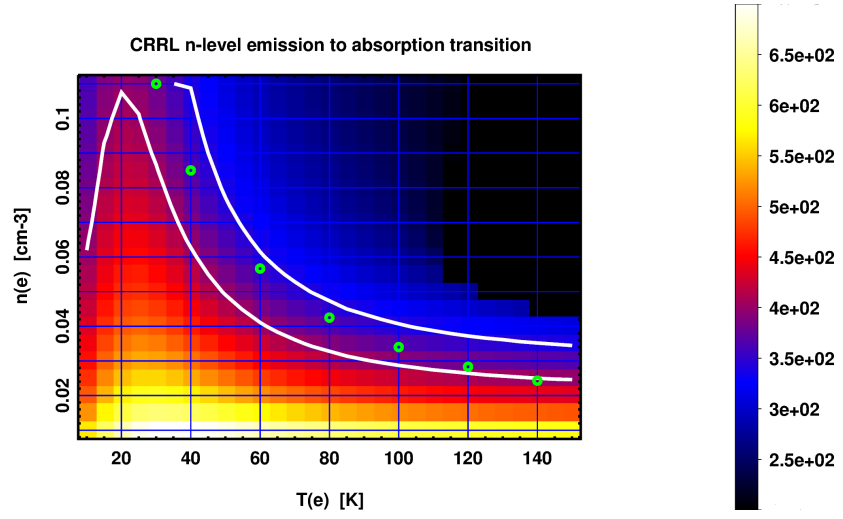


Figure 12. CRRL n-level transition value as a function of T_e and n_e for our model grid. The white contours are drawn for $n=340$ and $n=400$. This n-range for the transition corresponds to the range for our measurements. The green circles highlight values of constant electron pressure $p_e = 0.04 \times 85 = 3.4 \text{ K cm}^{-3}$. This shows that the transition n-level value is a good indicator of the electron pressure in the 20-140 K range.

This paper has been typeset from a \TeX / \LaTeX file prepared by the author.

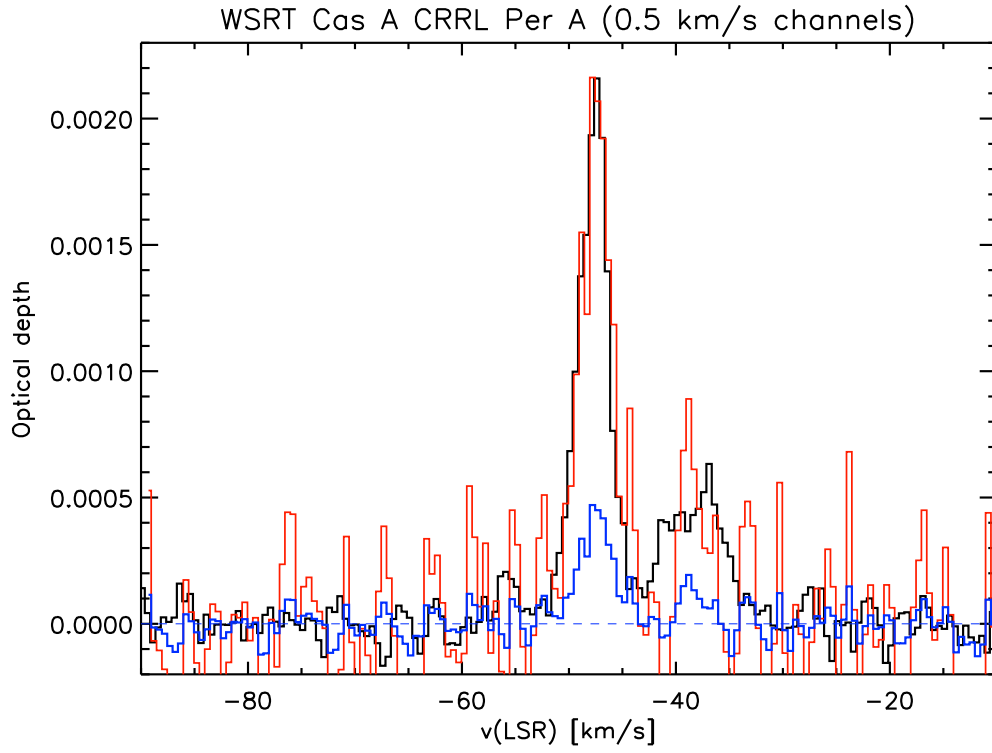


Figure 13. Stacked WSRT P-band spectrum. The spectrum shows the CRRLs (black) and HRRLs (blue) overlaid. The HRRL spectrum is shifted by -149.4 km s^{-1} to match CRRL spectrum. This difference corresponds to the difference in rest frequencies for the HRRLs and CRRLs. In addition in red we show the HRRL spectrum scaled by a factor 4.6 to match the CRRL and HRRL peaks for the -47 component.

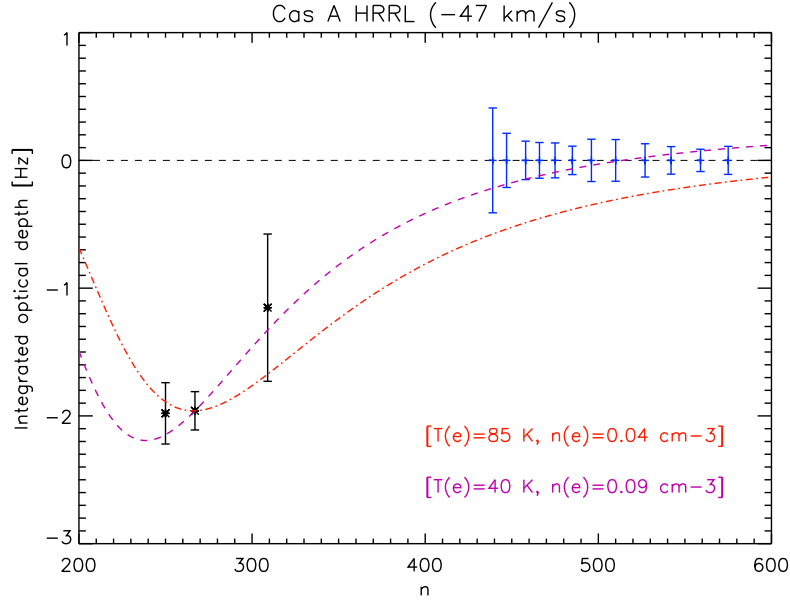


Figure 14. Cas A HRRL integrated optical depth vs. quantum number (n) for -47 km s^{-1} cloud. The three detections (black data points) are from this work, Oonk et al. (2015) and Sorochenko & Smirnov (2010). The blue bars show the 3σ HRRL upperlimits obtained from our LBA measurements (Table 6). The red curve shows the scaled HRRL model upon assuming that the same physical parameters ($T_e=85 \text{ K}$ and $n_e=0.04 \text{ cm}^{-3}$) as the best fit CRRL model. The scaling is done by normalizing this model at the WSRT data point and gives $EM_H=0.0036 \text{ cm}^{-6} \text{ pc}$. If we set $L_H=L_C$ we find $n_{HII}/n_{CII}=0.06$. Alternatively $L_H/L_C=0.06$ if we set $n_{HII}=n_{CII}$. This model does not fit the LBA upperlimits. Investigating the full HRRL grid we find that temperatures and densities in the range $T_e=30\text{-}50 \text{ K}$ and $n_e=0.065\text{-}0.11 \text{ cm}^{-3}$ are able to fit both the measurements and the upperlimits. The purple curve shows an example with $T_e=40 \text{ K}$, $n_e=0.09 \text{ cm}^{-3}$ and has $EM_H=0.0014 \text{ cm}^{-6} \text{ pc}$.